2015

Kitchen 2.0: Investigation of the Effect of Ventilation on Indoor Air Quality

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Recommended Citation

Whelan, Kelli Marie, "Kitchen 2.0: Investigation of the Effect of Ventilation on Indoor Air Quality", Open Access Master's Report, Michigan Technological University, 2015.
https://doi.org/10.37099/mtu.dc.etdr/57

KITCHEN 2.0: INVESTIGATION OF THE EFFECT OF VENTILATION ON INDOOR AIR QUALITY

By

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A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Environmental Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2015

This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Environmental Engineering.

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For my family.

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Abstract

Even in today's technology-filled world, nearly half of the global population still relies on some form of biomass to meet their daily energy requirement. Currently, improved combustion technologies (improved cookstoves) the most common intervention to reduce fuel usage and to reduce human exposure to harmful products of incomplete combustion. This report explores an alternative option to cookstove replacement: ventilation as a low-cost, low-impact solution for health risk reduction.

1 Introduction

Nearly half of the world uses some form of biomass combustion to meet their basic energy needs, such as cooking, light, and heat. Biomass fuels are largely unprocessed and non-uniform, and include crop residues, dung, wood, charcoal, and in some cases coal. Combustion of these fuel sources under the best of cases would still lead to a range of products of incomplete production (PICs), but unfortunately for the under-developed world, highly efficient cookstoves are either unavailable or not used. Instead, most of the world's heating, lighting and cooking is performed over three stones or a mud-clay u-shape, here called a traditional cookstove. While a well-tended traditional cookstove can achieve a similar level of combustion performance as some of the engineered cookstoves available on the market, usage with any cookstove is highly user-dependent and exposure to any products of combustion has been proven life threatening, especially to women and young children. In this study, the effect of ventilation and kitchen design on the ambient concentration of particulate matter and carbon monoxide was investigated, with hopes that a simple configuration would decrease contaminants as much as the best cookstove interventions, yet offer more likely use and long-term benefits.

1.1 Background

Approximately 3 billion people worldwide continue to rely on unrefined fuel sources, also known as biomass, to meet their daily household energy needs (WHO, 2015). Biomass ranges from completely unprocessed fuel sources such as animal dung and crop residue to more refined fuels such as charcoal, coal, and kerosene. However, burning unrefined fuel sources is generally an incomplete combustion process, leading to the emission of carbon dioxide (CO_2), carbon monoxide (CO), a variety of particulates including ultrafine particulates and polycyclic aromatic hydrocarbon, and in the case of coal, sulfur and nitric compounds (Smith, et al. 2004). These are also known as products of incomplete combustion (PIC), and are the primary components constituting household air pollution (HAP).

While the exact daily dosages of atmospheric pollutants are difficult to determine, one thing is clear: acute and chronic exposure to air pollutants result in severe health risks. Exposure to HAP constitutes the third highest ranked global risk factor for disease burden as of 2010 (Lim, et. al. 2012) and is the cause of approximately 4.3 million deaths annually (WHO 2015). Children under five years of age are on average 2.9 times more likely to develop an acute lower respiratory infection (ALRI) than children who are not chronically exposed to HAP. Both men and women have a higher risk of developing life-threatening diseases such as chronic obstructive pulmonary disease (COPD), lung cancer, ischemic heart disease (IHD), and strokes than people not exposed to products of biomass combustion (WHO 2014). Although women's personal exposure to particulate matter with an average aerodynamic diameter of 2.5 micrometers is over 100 $\mu g/m^3$ higher than men (WHO 2014), men have a higher percentage of deaths attributable to smoke exposure (46% of total HAP deaths) due to disease susceptibility (WHO 2014). Acute and chronic exposure to PIC can also lead to a host of debilitating and potentially deadly respiratory, skin, and eye diseases. PIC has also been linked to low birth rates and an increased risk of stillborn births (Bruce et al. 2002). A 50-90% reduction in typical HAP levels is critical to achieving desired short- and long-term health benefits (Pinkerton and Rom 2013). Outside of the health spectrum, fuel gathering detracts from educational and entrepreneurial opportunities, has caused widespread deforestation, and can be dangerous for gatherers (Global Alliance 2015). Worldwide PIC emissions also contribute to climate change, although their exact contribution is still unknown.

Many indoor air quality improvement initiatives focus on the pollution source, the cookstove. This is done through increasing the thermal and combustion efficiencies by changes in the combustion chamber and the cookstove body. Decreasing the presence of pollution at its source has many positive attributes, but requires some initial financial investment either by the cookstove user, his or her family, or some form of cost subsidization. Depending on the user's financial situation, this may be a large barrier to adopting cleaner cooking technologies or prevent their use of them all together. Also, improved cookstoves usually require some behavior modification on the user's part, either through cookstove use or regular maintenance; these can be additional barriers to long-term adoption. Finally, studies have shown that even when improved cookstoves are purchased, or even cleaner forms of energy like LPG gas are in use, users will "stack" cooking technologies: use different cooking methods for different dishes or when cooking for large groups of people. Such user realities decrease the actual effect of improved combustion technologies after distribution and thus their viability as a solution (Pinkerton and Rom, 2013; Rehfuess et al. 2014).

1.2 Solution Development and Testing

Engineered or improved cookstove research and development has changed drastically over the past forty years, and has had a range of social and societal implications for both the under-developed world and Earth as a whole. Starting in the 1970's environmentally consciousness era, preliminary studies and advances were focused on the improvement of combustion efficiency to mitigate global deforestation. From that initial standpoint, cookstove advances have evolved alongside monitoring technology and a deeper understanding of HAP health impacts. Interventions are currently focused on the reduction of emissions, as decreasing contaminants at the source are the only real way to guarantee a healthy level of exposure (WHO 2014). Today a seemingly infinite range of cookstoves exist on today's market: wood-burning, natural draft top-lit gasifiers (TLUD), solar cookers, briquette ovens, highly engineered cookstoves, local knockoffs, and of course, the ubiquitous traditional three stone or clay stoves.

Testing and accreditation has evolved as well. In February 2012, a twenty-two country collaboration passed the initial framework for internationally recognized cookstove testing procedures and rankings through the International Organization for Standardization (ISO) (United Nations Foundation 2015). The framework assigns the various aspects of cookstoves (fuel efficiency, total emissions, indoor emissions, and safety) to one of five tiers (Tier 0 to Tier 4), Tier 0 being the lowest performance and Tier 4 the highest. It relies primarily on the results from the Water Boiling Test (WBT) (PCIA 2014), a laboratory-based protocol, along with the newly developed Biomass Stove Safety Protocol. The International Workshop Agreements IWA 11:2012 makes excellent progress towards accurately representing the function and aspects of biomass cookstoves worldwide, aiding consumer and policy makers' decisions (United Nations Foundation 2015).

Unfortunately, the IWA 11:2012 framework relies on a laboratory run protocol: highly controlled conditions with cured fuel. This methodology was created to quantify small changes in the physical structure of a cookstove and accurately compare different cookstove designs, not to replicate conditions seen in the field. Other less controlled testing protocols exist, but these receive less attention due to the heterogeneity (increase in variance) inherent in the tests. The Controlled Cooking Test (CCT; Bailis 2004) recreates a cooking event of a set meal instead of boiling and simmering water, but is still conducted under controlled circumstances. The Uncontrolled Cooking Test (UCT; Robinson et al.) allows users to use the cookstove as they would normally in their home. The Kitchen Performance Test (KPT; Bailis et al. 2007) is the final validation step conducted in the field, and combines quantitative and qualitative assessment techniques during real use conditions. These protocols were created with the intent that they be used in succession: starting with the WBT during design work iterations and ending with the KPT to assess an interventions true impact (PCIA 2014). However, given the amount of emphasis currently placed on WBT results, it is this author's opinion that cookstove efficacy will continue to be judged by unrealistic standards for the foreseeable future.

The polar opposite approach is in-field investigation. These studies capture the exact conditions and functionality of cookstoves after introduction or adoption, yet are just as problematic. Between the confounding factors that impact combustion and the wide variability in domestic practices, large samples are needed to compensate for the enormous variance in the data. This requirement exponentially increases the cost and time needed to conduct a field study, both of which are limiting factors to any type of research. Hence field investigations tend to provide a limited snapshot of a location or region, and rarely use the same methodology, making any direct comparison between studies difficult. Also, until recently, air quality measurement instrumentation had not been developed to withstand the extremes experienced in field testing and monitor the concentration levels of HAP common in many homes throughout the developing world. No in-kitchen field measurement protocols have been developed and internationally agreed upon, although a few practices have been repeated, for example single monitors are placed 1.5 meters horizontally from and 1.5 meters above the cooking surface or personal exposure monitors are worn by the cooks themselves.

1.3 Kitchen 2.0

A more transferrable solution to human exposure to HAP could be to improve the ventilation of the cooking space through changes in the kitchen structure itself. In developed countries, forced ventilation and fume hoods are requirements in areas where high levels of contaminants are being generated and these engineering controls require no or very little behavioral modification from the workers in the area. The installation of electrically powered fans in developing country kitchens is not feasible and the successful implementation of chimneys has had mixed success. However, the strategic placement of “windows” (openings without glass) and doors informed by prevailing wind patterns is seemingly inexpensive, transferrable, and locally sustainable. The idea of ventilation as a solution to human HAP exposure served as the motivational basis for this work: the Kitchen 2.0 project.

The objectives of Kitchen 2.0 were to:

- Merge field and laboratory testing methodologies to better understand the impact an improved cookstove would have on the indoor air quality in developing country kitchens.
- Determine if ventilation plays a significant role in indoor air pollution and if so, develop simple kitchen construction recommendations based on the testing results.
- Gather data for as many structural configurations as possible to validate a computational indoor air quality model of the space. The computational model was developed for the U.S. Environmental Protection Agency (U.S. EPA) People, Prosperity and the Planet (P3) Competition and is not explained further in this report.

This investigation was initially conducted as part of the team's participation in the 2013 U.S. EPA annual P3 Competition, and was funded by grants from the U.S. EPA and the National Science Foundation (NSF). The experimental portion discussed here was part of a larger, holistic analysis of indoor air quality, which included a social survey of homes and cooks from 12 countries around the world and a computational fluid dynamics (CFD) model of the model kitchen used during the experimental portion. The social survey and the CFD model will not be discussed further here; however a summary of the complete Kitchen 2.0 project has been published in the International Journal of Engineering Service Learning (Ruth, et al. 2014).

2 Research Methodology

The Kitchen 2.0 project attempted to bring aspects of real-world situations to a controlled laboratory environment. This is illustrated by both the model testing facility and the experimental protocol. The testing facility allowed for a higher degree of control over the environmental factors that may affect HAP concentrations and transport within the test kitchen. The test kitchen dimensions and roofing materials reflected those commonly seen throughout the developing world, and specifically in rural Tanzania. Ambient concentrations of HAP, specifically particulate matter with an aerodynamic diameter of equal to or less than 2.5 micrometers ($PM_{2.5}$) and carbon monoxide (CO), were recorded in real-time in 15 different locations inside the test kitchen. Field measurements are generally restricted to one location near the cookstove or attached on the cook's person; the additional monitors in the test kitchen provided a higher resolution of the HAP spatial variability during and after a cooking event. Lastly, the CCT protocol was used in this study. The CCT protocol provides more insight into the functionality of the cookstove than the WBT protocol by utilizing a standardized meal, rather than boiling and simmering water. Unfortunately, variability is also a real-world aspect that was added as laboratory boundaries were expanded in this investigation (see Section 4 for discussion on this topic).

2.1 Physical Model Setup

Because testing was conducted during the inclement winter months, the Kitchen 2.0 testing facility was constructed indoors in a repurposed manufacturing building (now the Advanced Power Systems Research Center (APSR)) near Hancock, Michigan. The Kitchen 2.0 facility consisted of model kitchen, with a size and shape representative of kitchens found in rural Tanzania as well as other countries worldwide, situated inside of a ventilated clean room as shown in Figure 2.1 and Figure 2.2. The clean room, designed online through a portable boat shelter supplier, was needed to collect the HAP and vent all emissions outside of the APSR building via an industrial exhaust fan (constant fan speed: approximately 6000-6500 cfm) located under one of the clean room gables. It also provided a level of fire control as the walls of the clean room were made of fire-retardant polyurethane tarp. Any gaps in the tarp walls and edges along the floor were taped shut. Due to budget and space restrictions, the clean room dimensions were just large enough to accommodate the test kitchen and some additional instrumentation. It was assumed that the exhaust fan velocity was high enough to remove all of the emissions as they exited the test kitchen, preventing circulation within the Kitchen 2.0 testing facility, but this was never confirmed experimentally. See Table 2.1 for the clean room dimensions.

Table 2.1 Dimensions of the Kitchen 2.0 Clean Room and Kitchen Structure.

	Clean Room Dimensions		*Kitchen Dimensions*	
	Feet (ft)	*Meters (m)*	*Feet (ft)*	*Meters (m)*
Height at Apex	11.29	3.44	9.25	2.82
Wall Height	8.50	2.59	6.58	2.00
Length	20.00	6.10	11.98	3.65
Width	15.00	4.57	7.90	2.40
Volume (ft^3; m^3)	2968.75	84.07	748.80	21.14

The model kitchen was framed using construction grade lumber (see Table 2.1 above for the kitchen dimensions). The walls were constructed from 3 meter by 1 meter plywood sheets; these were screwed onto the frame for easy removal and reattachment. Like the clean room, gaps between the plywood sheets were sealed with duct tape (except the gap between the bottom sheet and the floor, which was minimal). The roof was initially made of corrugated aluminum sheeting, but was later replaced with a thatched roofing material to study the ventilation difference between traditional and modern construction materials. The space between the top of the walls and the gables at either end of the test kitchen were sealed with plastic sheeting and remained so throughout the data collection period. Likewise, the eaves (the space between the top of the walls and the edges of the roof) were sealed with plastic except when the eaves were tested as a ventilation factor. The windows (1 foot by 1 foot (30.48 cm by 30.48 cm) holes cut into six of the plywood panels) were either open or sealed closed with plastic, depending on the amount of ventilation desired. The door, roughly one third the length of the kitchen, was also sealed with plastic when minimal or no ventilation was desired. See Figure 2.1 below for reference.

Figure 2.1: Kitchen 2.0 in the clean room. Tarps were used to cover the door and windows so they could be opened or closed easily. Note the gables at either end were always sealed during testing, and the eaves were sealed unless otherwise specified (photo credit: author).

Figure 2.2. Inside Kitchen 2.0 facing the central monitor location, cookstove location is the corrugated metal zone in lower left (photo credit: author).

In an attempt to recreate natural wind conditions, two industrial pedestal fans at one end of the tent provided an artificial wind source when desired (high speed: 3000 cfm; low speed: 1800 cfm). The fans were located approximately two feet from and faced the left two windows depicted in Figure 2.3 (with arrows pointing inward), blowing air into the kitchen structure. An industrial exhaust fan, mentioned earlier, provided a continuous flow of air parallel to the long sides of the test kitchen). A complete diagram of the kitchen and its dimensions is located in Appendix A.

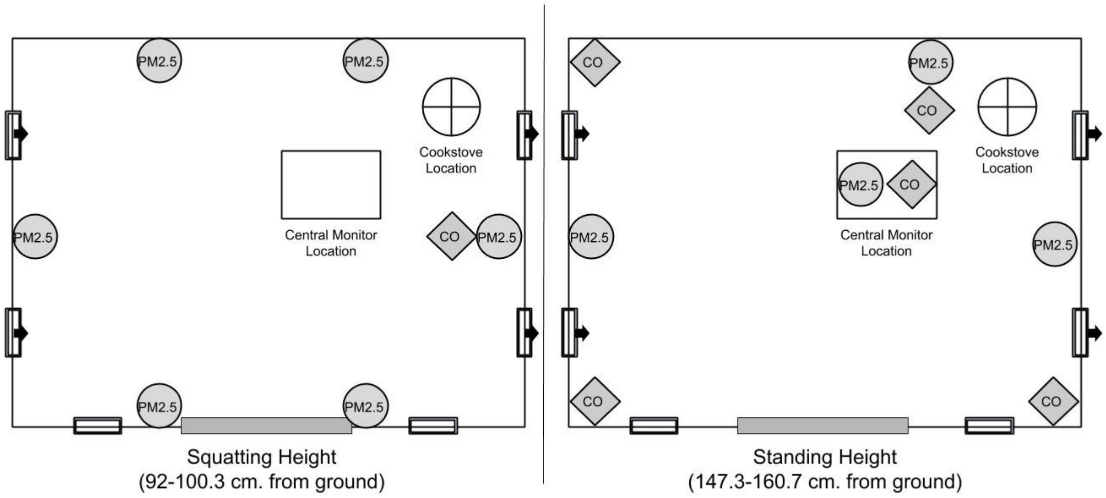


Figure 2.3: Monitor placement diagrams. The black arrows located at each of the windows indicate the general air flow direction and are not to scale. The "central monitor location" represents the location of the APS, Q-Trak, DustTrak, and anemometer in addition to the two field monitors displayed in Figure 2 b). Not shown: two CO monitors placed at either gable under the roof (273-274.3 centimeters from ground).

To determine the presence of HAP at specific locations within the kitchen and track their transport, a combination of small field monitors and more sophisticated instrumentation was used (see Table 2.2 for a complete list of the instruments used). This report will focus on the results from the University of California Berkley Particle and Temperature Sensor (UCB-PATS $PM_{2.5}$)

monitors (temperature and particulate matter with an aerodynamic diameter of 2.5 micrometers or less ($PM_{2.5}$)) and Lascar Electronics carbon monoxide monitors (CO), both of which are smaller, more robust monitors more commonly deployed in field research campaigns. The UCB-PATS $PM_{2.5}$ and CO monitors were placed around the structure in a grid pattern around the kitchen at two heights (approximately 30 centimeters and 60 centimeters off the ground), representing typical squatting and standing heights of cookstove users in developing countries (as shown in Figure 2.3 above). In addition, two carbon monoxide monitors were located at the gables at either end of the kitchen structure to determine if there was vertical stratification. The TSI aerodynamic particle sizer (particle size distribution), Q-Trak (CO), DustTrak (PM_{10}), anemometer, and one of each of the field monitors were co-located at approximately 1.5 meters from the cooking implement and about 1.5 meters off the ground at the central monitor location (see for reference). This distance is a common protocol in field data collection because it assesses the cook's exposure with minimal interruption and allows for some dilution with the surrounding, reducing the chance of sensor over-saturation. All monitors had previously been factory calibrated. In addition, the $PM_{2.5}$ and CO field monitors were removed three times during the testing period to download data and clean the sensors. The monitors were then re-zeroed according to the manufacturer's instructions prior to reinstallation.

Table 2.2: Experimental Monitors Used in the Kitchen 2.0 Project.

Measurand	*Monitor*	*Manufacturer*	*Sampling Frequency*	*Number of Monitors Used*
Air Flow	Hot wire anemometer	Lutron	10s	1
CO	EL-USB-CO300	Lascar Electronics	10 s	8
CO/CO_2	Q-Trak Indoor Air Quality Monitor, Model 7575	TSI, Inc.	5 s	1
PM (<0.523-19.81µm)	Aerodynamic Particle Sizer	TSI, Inc.	10 s	1
$PM_{2.5}$	UCB-PATS	Berkley Air Monitoring Group	1 min	10
PM_{10}	DustTrak Aerosol Monitor, Model 8520	TSI, Inc.	10 s	1
Temperature	Q-Trak, UCB-PATS	TSI, Inc., Berkley Air Monitoring Group	10 s	11
Weight	Top pan scale		As needed	1
Wood Moisture	Moisture Meter, Model MO220	Extech Instruments	3 times per trial	1

2.2 Testing Protocol

The CCT methodology was selected over the WBT for Kitchen 2.0 because the CCT reconstructs a real world cooking event while being a rigorous testing protocol. For this investigation, a cooking event reflects the time and energy required to cook two cups of white rice in four cups of water until all water has evaporated or been absorbed, and the cooked rice began to stick to the bottom of a 14.5 liter aluminum pot. Two to five iterations were completed of the same structural configuration, cookstove used, and artificial wind speed, with an average of three trials per setup. The researchers rotated cooking and observation duties throughout the data collection process. Most of the "cooks" had previous experience lighting and maintaining a campfire, which is similar to the three stone cookstove, but only two had experience operating an improved cookstove prior to the testing period.

Prior to lighting the fire, all raw food ingredients, kindling and newspaper, firewood, and cooking vessels were weighed and recorded to the nearest tenth of a gram. Unless specified as a wet fuel test, cured American hardwood was used for the primary fuel source (average wood moisture was approximately 9%). All firewood was split and cut to size according to the improved cookstove manufacturers' recommendations. For the wet fuel tests, the cured firewood was re-saturated overnight so that the wood moisture content was approximately twice its original reading (on average 19% moisture content). Kindling consisted of either smaller pieces of the firewood or pieces of American softwood species. The small field monitors continuously recorded the concentration of $PM_{2.5}$ and carbon monoxide throughout the space at preset sampling intervals (see Table 2.2 for reference). The APS, Q-Trak, DustTrak, and anemometer were turned on approximately five minutes prior to lighting the fire for each trial to record the background contaminant concentrations, and then continued to collect removal and decay data for the analytes over a period of about 20 minutes after the fire had been extinguished (or when the ambient concentration of carbon monoxide detected by the Q-Trak returned to pre-trial levels).

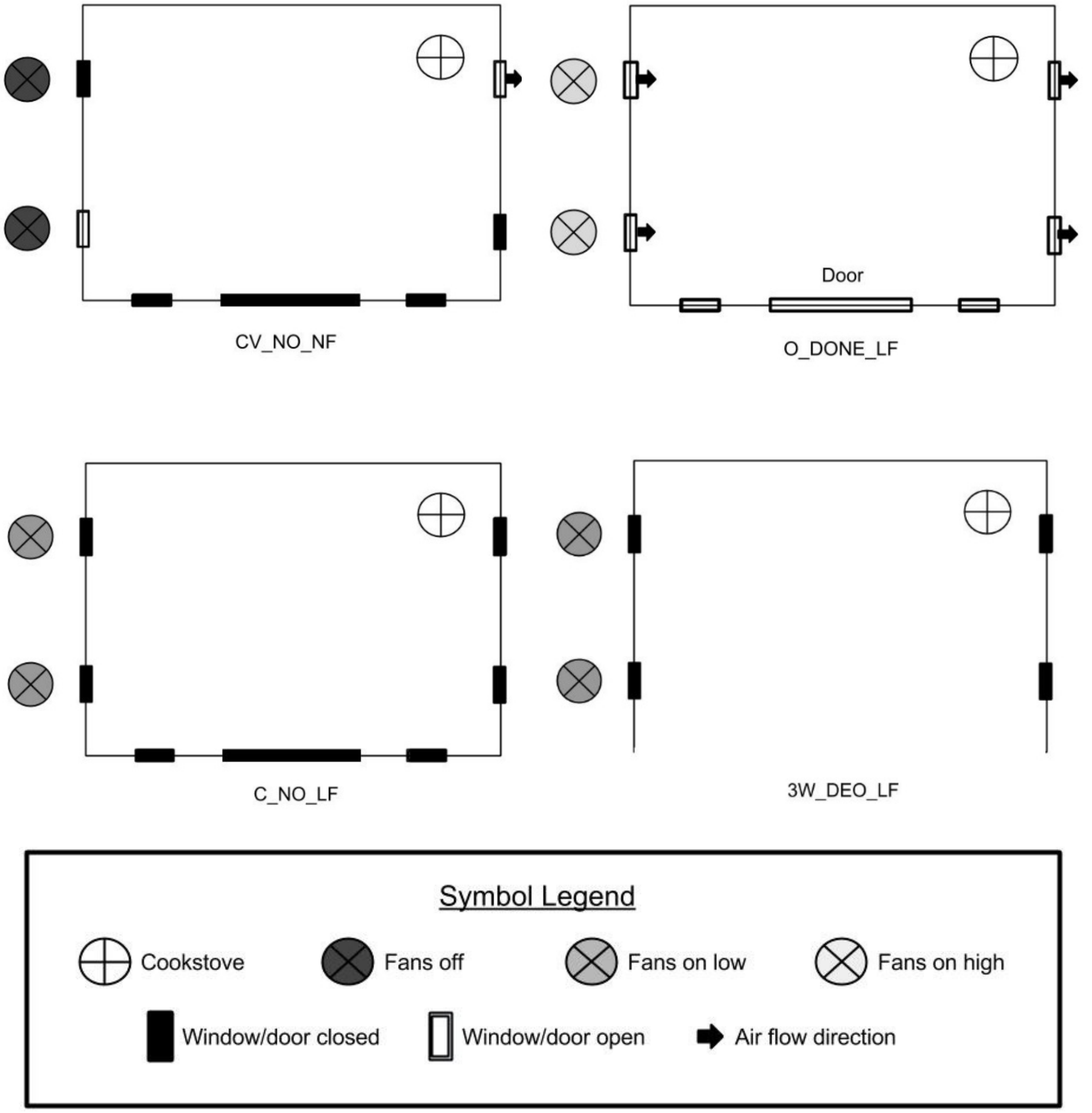
Three cookstoves were included in the investigation based on their extensive worldwide distribution and use: one traditional three-stone stove and two improved cookstoves (StoveTec GreenFire Combo 2 Door Biomass Cook Stove and Envirofit G3300 Cook Stove; hereafter referred to as StoveTec and Envirofit). For the three-stone stove, three large rocks were arranged in a triangle so the pot was supported by all three. Kindling was wrapped in newspaper and placed on the ground under the pot, and then one piece of wood was placed between each of the stones (three total) so the tips overlapped on top of the kindling/newspaper bundle. The kindling/newspaper bundle was ignited first, and the wood pieces were pushed into the flames as the fuel burned. If the fire began to burn less vigorously or failed to ignite, the embers were fanned and/or addition kindling and newspaper was added. For both of the improved cookstoves, kindling was wrapped in newspaper and placed in the combustion chamber. The ends of one or two pieces of firewood (depending on the thickness of the wood) were placed on top of the fire starter bundle, and then the bundle was ignited. The ends of the firewood were pushed further into the combustion chamber as the fuel was consumed. Again, the fire was fanned if the flames began to die down, kindling and newspaper were added if necessary. To extinguish the fire, the burning pieces of wood were removed from the cookstove, blown out, and then the larger embers were extinguished by tapping them against the ground. The smaller embers and remaining smoldering fuel was allowed to burn out. All unburned fuel, char, and ash, as well as the cooked rice, were then collected, weighed, and recorded to the nearest tenth after the die down period mentioned earlier.

In addition to varying the cookstove used, eleven different physical structures of the modular kitchen were tested during the data collection period. This resulted in nineteen different combinations of cookstoves and structural configurations; trials for each combination were repeated two to five times, with an average of three trials. These combinations are described below in Table 2.3. A selected portion are illustrated below in Figure 2.4. The ambient temperature and humidity were not varied due to a lack of time and resources.

Table 2.3: Number of Trials per Cookstove and Structural Variation.

		TSF	*TSF(W)*	*EF*	*EF(D)*	*EF(O)*	*ST*	*ST(W)*
CV	NO_NF	3	3	3			3	
	NO_HF			3				
	DONE_LF				1	2		
	DONE_HF			3	1			
	T_NO_NF							2
O	DONE_LF	3		3			3	
C	NO_LF	3		3			3	
	T_NO_NF	5						
E	NO_LF						3	
3W	DEO_LF			3				
2/3W	DEO_LF			3				

CV: Two windows open, diagonally across kitchen; **O**: All windows and door open; **C**: All windows and doors sealed closed; **E**: Eaves under roof open; **3W**: One side of kitchen open; **2/3W**: All walls at 2/3 original height; **DEO**: Door and eaves under roof open; **DONE**: Door open, eaves sealed closed; **NO**: No other outlets; **T**: Thatched roofing instead of corrugated metal; **NF**: Fans off; **LF**: Fans on low; **HF**: Fans on high; **TSF**: Three-stone fire; **TSF(W)**: Three-stone fire, wet wood; **EF**: Envirofit G3300 Cook Stove; **EF(D)**: Envirofit Cook Stove place next to door; **EF(O)**: Envirofit Cook Stove placed in corner opposite original position; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt; **ST(W)**: StoveTec Cook Stove, wet wood



CV: Two windows open, diagonally across kitchen; **O:** All windows and door open; **C:** All windows and doors sealed closed; **3W:** One side of kitchen open; **DEO:** Door and eaves under roof open; **DONE:** Door open, eaves sealed closed; **NO:** No other outlets; **NF:** Fans off; **LF:** Fans on low

Figure 2.4: Pictorial representation of four Kitchen 2.0 configurations.

The CCT requires the physical presence of the cook (or researcher) to tend the fire in order to complete each cooking event in a timely and accurate manner. Because this investigation was not conducted in a ventilated fume hood, the researchers were exposed to acute, high levels of HAP. To reduce the risk of injury, researchers were required to wear safety glasses and particle respirators (3M) during all trials. Researchers also exited the clean room to fresh air immediately after extinguishing each fire. Hot embers and unburned wood were handled with tongs, and hot cooking implements were allowed to cool to the touch. Additional fire control measures included lining the walls around the cookstove location with metal paneling, a fire extinguisher located at the entrance of the modular kitchen, and using fire-retardant materials for the thatched roofing and clean room wall material. Researchers never worked alone, and the ambient CO concentration was measured by a separate household monitor placed in the kitchen structure.

3 Results

$PM_{2.5}$ and CO were monitored in real-time in a grid pattern at the walls of Kitchen 2.0, as well as at a central testing location approximately 1.5 meters out by 1.5 meters up from the typical cookstove location (see Figure 2.3 for reference). The data from all monitors was downloaded three times during the testing period. The $PM_{2.5}$ and CO monitors were then zeroed in a clean environment before being replaced in their original positions; the $PM_{2.5}$ monitors were also cleaned prior to reinstallation according to the manufacturer's specifications. Start and stop times for igniting and extinguishing the trials were recorded manually during the testing period. All data was smoothed using a three minute moving average and was normalized to the length of its respective trial.

3.1 Controlled Cooking Test Results

Unlike the WBT, minimal inferences into a cookstove's efficiency can be drawn using the CCT protocol unless testing is conducted under a hood system. Since the focus of Kitchen 2.0 was to better understand HAP concentrations in a space, not to serve as a cookstove efficiency test, efficiency factors for the individual cookstoves were not calculated (these may be found elsewhere in literature; Jetter and Kariher, 2009, for example). However, the CCT does collect three quantities of interest: the amount of time required to complete a cooking task (hereafter referred to as "time to cook") and the amount of fuel used per meal. When the amount of fuel used during each trial is normalized to the mass of food cooked, it is called the specific fuel consumption. Additionally, the hands-on nature of Kitchen 2.0 allowed the researchers to gather valuable qualitative data from the cooking experience; these have been paraphrased in Section 4.2.1.

During the Kitchen 2.0 testing period, no significant difference was seen in the cooking times between cookstoves, even when the fuel was wet. However, the increased wood moisture caused both the equivalent fuel consumed and the specific fuel consumption to be dramatically higher for the wet fuel trials than the dry fuel trials. As the specific fuel consumption is the primary indicator for cookstove performance in the CCT, fuel quality is the only significant difference in overall performance. These quantities are displayed in Table 3.1 with one standard deviation.

Table 3.1. Time to Cook and Specific Fuel Usage for Three Stoves.

	Time to Cook (min)	*Equivalent Dry Wood Consumed (g)*	*Specific Fuel Consumption (g fuel/kg food cooked)*	*Average Fuel Usage (from literature)*
TSF (n=13)	26 ± 7	1659 ± 306	1334 ± 262	1.57 ± 0.497 kg PEM^{-1} [a]
TSF(W) (n=3)	25 ± 8	4460 ± 448	3663 ± 337	
ST (n=12)	23 ± 5	1718 ± 267	1379 ± 204	
EF (n=25)	21 ± 2	2126 ± 389	1744 ± 342	

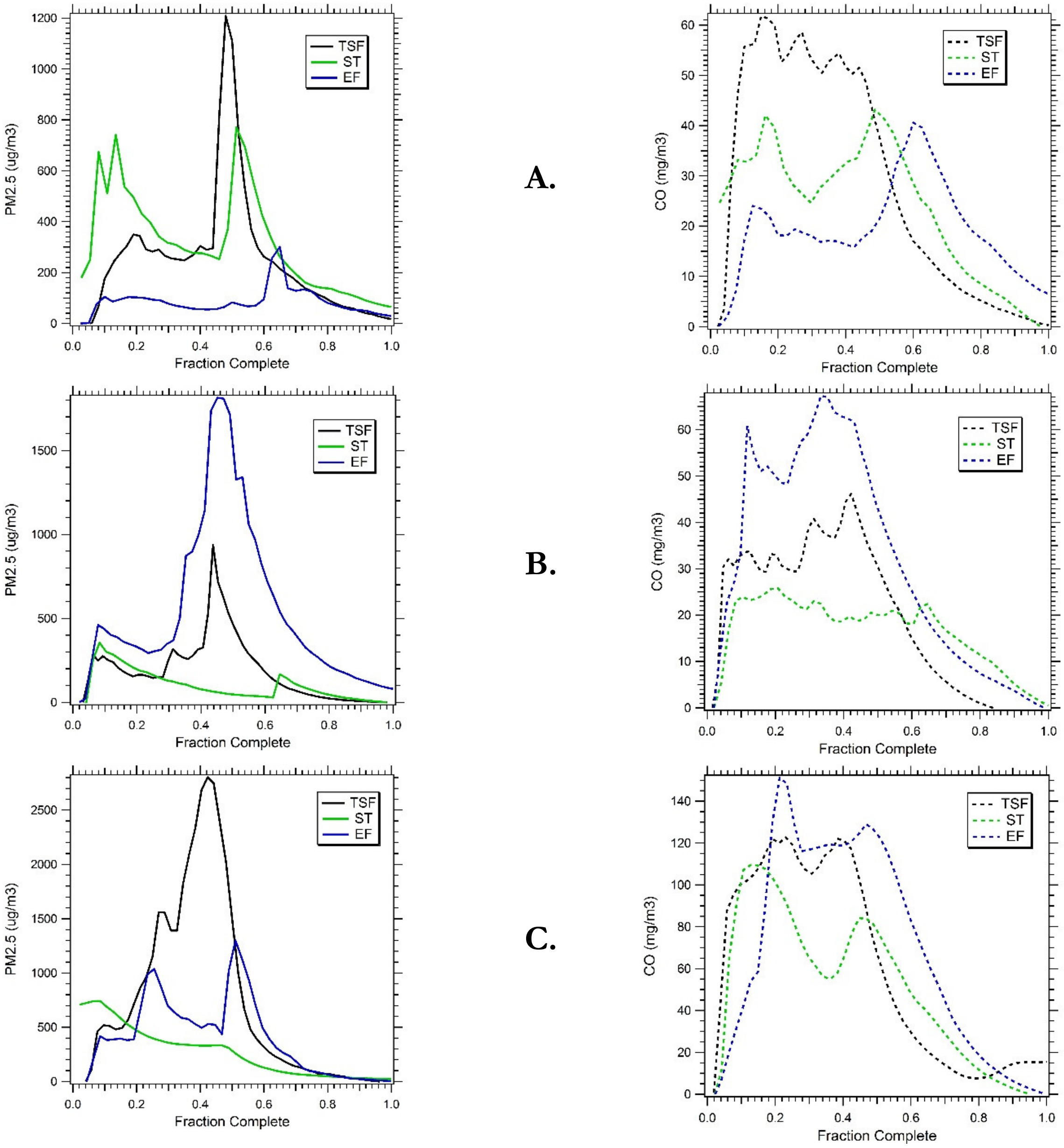
TSF: Three-stone fire; **TSF(W)**; Three-stone fire, wet wood; **EF**: Envirofit G3300 Cook Stove; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt

[a] Granderson et al. 2009: kilograms of wood used per person equivalent meals.

3.2 Concentration

Periods of interest in the data were selected through graphical analysis of the $PM_{2.5}$ and CO data from all 56 trials. The $PM_{2.5}$ data shows a clear bimodal trend:

one peak occurring shortly after igniting the fuel (0 to 0.35 fraction complete) and one upon extinguishing the fire (0.35 to 0.75 fraction complete). The third $PM_{2.5}$ time period (0.75 fraction complete to trial end) is assumed to be the decay and/or removal time of the contaminant, either through dry deposition or removal by the industrial exhaust fan. The CO data showed only one spike in concentration. The time periods of interest for the CO data were from 0 to 0.68 fraction complete (while the cookstove was lit), and from 0.68 fraction complete to trial end (assumed to be the decay/removal period). Unlike particulate matter, the decay of CO is attributed to forced removal by the industrial exhaust fan or through leakage through gaps in the clean room structure. See Figure 3.1 examples from three structural configurations, and Appendix B and Appendix C for trial-length, full kitchen average concentrations of $PM_{2.5}$ and CO, respectively.



CV: Two windows open, diagonally across kitchen; **O:** All windows and door open; **C:** All windows and doors sealed closed; **DONE:** Door open, eaves sealed closed; **NO:** No other outlets; **NF:** Fans off; **LF:** Fans on low

Figure 3.1: Particulate matter ($PM_{2.5}$) (left) and carbon monoxide (CO) (right) full kitchen concentrations for three structural configurations. Each chart shows the results of one trial: A. CV_NO_NF, B. O_DONE_LF, C. C_NO_LF.

3.2.1 HAP Average for Full Kitchen

The WHO recommends a 50-90% improvement in emissions from the three-stone cookstove baseline in order to prevent serious health risks (WHO, 2015). Since emissions should be closely related to exposure, one would expect that a similar reduction in exposure would be necessary to ensure the occupants' health.

Little or no improvement in HAP was seen for one configuration regardless of the cookstove used: the all closed structural configuration (C_NO_LF), which is a common occurrence around the world. If the three-stone cookstove (TSF) is simply replaced with an improved combustion model, the Kitchen 2.0 results show that the reductions in the mean $PM_{2.5}$ and CO concentrations do not meet the WHO recommended 50-90% reduction in $PM_{2.5}$ and CO (see Table 3.2 below). For absolute values, see Appendices B and C.

Table 3.2: Percent Change from the Three Stone (TSF) Geometric Mean.

	$PM_{2.5}$		CO	
	ST	*EF*	*ST*	*EF*
CV_NO_NF	-23.1	-66.7	-38.0	-46.8
O_DONE_LF	-69.8	-43.9	-32.0	5.6
C_NO_LF	6.3	26.4	-9.7	25.2

CV: Two windows open, diagonally across kitchen; **O**: All windows and door open; **C**: All windows and doors sealed closed: **DONE**: Door open, eaves sealed closed: **NO**: No other outlets: **NF**: Fans off: **LF**: Fans on low; **EF**: Envirofit G3300 Cook Stove; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt

The greatest reduction in HAP was found by varying the cookstove and the structural configuration relative to a baseline, and then comparing percent changes in mean $PM_{2.5}$ and CO concentrations (Table 3.3). The combination of the traditional, three stone cookstove (TSF) in a completely closed space (C_NO_LF) was selected to be the baseline combination as it represents no intervention (cookstove replacement or ventilation adjustment).

Table 3.3: Percent Change in HAP from a Closed, Three-Stone Fire Configuration.

		$PM_{2.5}$ (reference: 291.1 μg/m^3)				*CO (reference: 57.1 mg/m^3)*			
		TSF	*TSF(W)*	*ST*	*EF*	*TSF*	*TSF(W)*	*ST*	*EF*
CV	**NO_NF**	-38.9	25.1	-53.1	-79.6	-35.8	-14.8	-60.2	-65.8
	NO_HF				-38.9				-21.6
	DONE_HF				-48.7				-48.2
	DONE_LF				-47.6				-59.8
O	**DONE_LF**	15.2		-65.2	-35.4	-50.0		-66.0	-47.1
C	**NO_LF**	0.0		6.3	26.4	0.0		-9.7	25.2
	T_NO_LF	-36.8				-52.6			
E	**NO_LF**			-79.6				-46.5	
3W	**DEO_LF**			-55.4					-59.7
2/3W	**DEO_LF**				-55.0				-45.7

CV: Two windows open, diagonally across kitchen; **O**: All windows and door open; **C**: All windows and doors sealed closed: **E**: Eaves under roof open: **3W**: One side of kitchen open: **2/3W**: All walls at 2/3 original height; **DEO**: Door and eaves under roof open: **DONE**: Door open, eaves sealed closed: **NO**: No other outlets: **T**: Thatched roofing instead of corrugated metal: **NF**: Fans off: **LF**: Fans on low; **HF**: Fans on high; **TSF**: Three-stone fire; **TSF(W)**: Three-stone fire, wet wood; **EF**: Envirofit G3300 Cook Stove; **EF(D)**: Envirofit Cook Stove place next to door; **EF(O)**: Envirofit Cook Stove placed in corner opposite original position; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt; **ST(W)**: StoveTec Cook Stove, wet wood

For a majority of the results above, the combined use of an improved cookstove and an increase in ventilation (air exchanges per hour) did result in the HAP reductions necessary. The greatest improvement in air quality was seen with the combination of cross-kitchen ventilation (CV_NO) and the Envirofit G3300 cookstove (EF), even with no artificial wind (NF). It is important to note, however, that the percent changes above were calculated from whole room averages and may not accurately capture the interspatial differences in HAP in the model kitchen. Certain locations, especially near the cookstove while it was lit, may not experience the amount of air quality improvement reported in Table 3.5.

3.3 Ventilation

Theoretically, increasing the air removal rate will decrease the occupant exposure to HAP in a kitchen or living area. To see if this was true for Kitchen 2.0, air exchange rates were calculated for each of the structural configurations. The decay rates for both CO and $PM_{2.5}$ were also found.

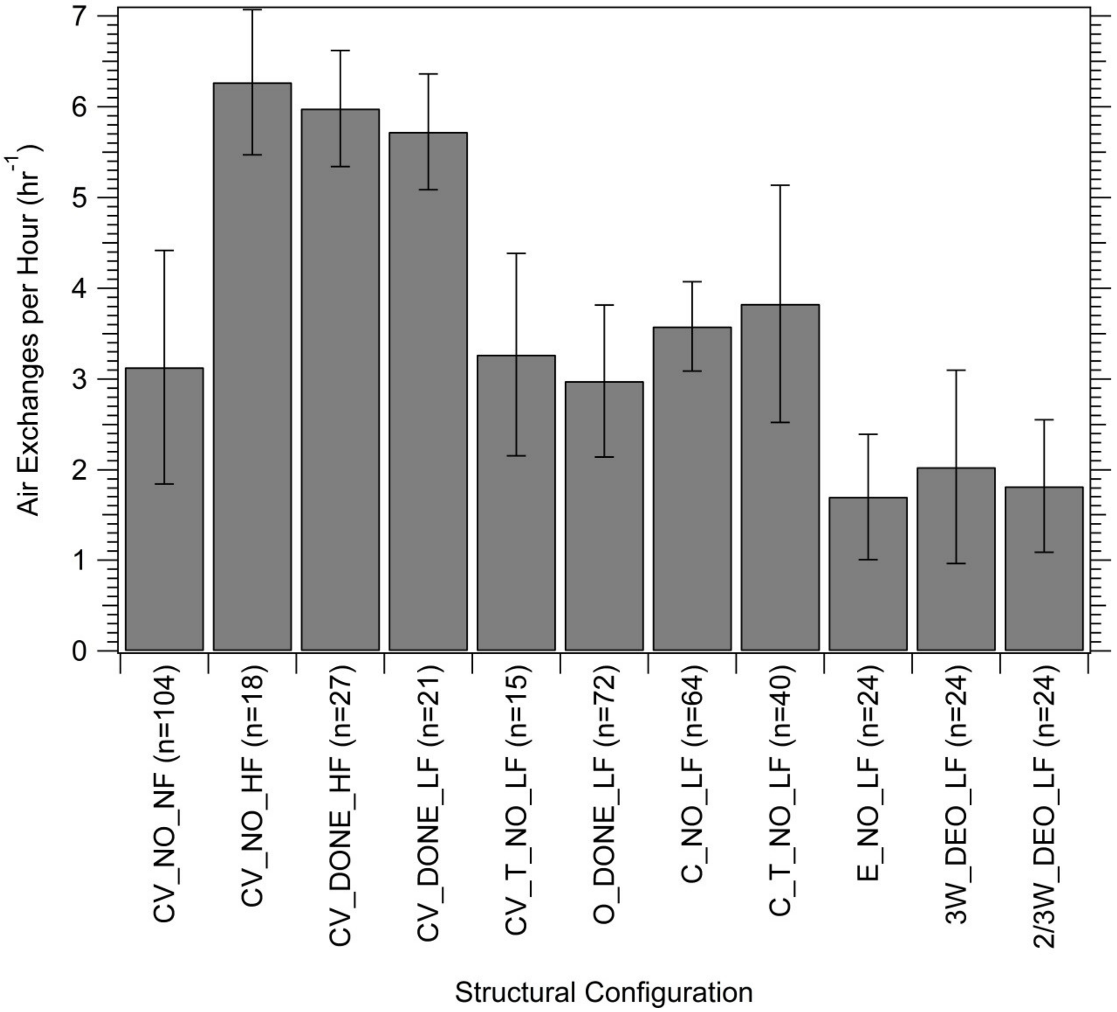
3.3.1 Air Exchange by Configuration

Carbon monoxide is a stable, generally non-reactive gas at short time intervals that is produced when there is insufficient oxygen available during the combustion process. Due to its physical characteristics in comparison to other gases present in the air, it can be assumed to be well mixed in a space. The combination of its physical and reactivity characteristics make CO an ideal tracer gas, enabling the calculation of the venting quality of each structural configuration. The venting quality, represented by the number of air exchanges per hour, was determined for each of the nine CO monitors using the Basic Room Purge as reported in Grabow, et al. (2013) and shown below:

$$D_t = \left[\frac{V}{Q}\right] \cdot ln\left[\frac{C_{initial}}{C_{ending}}\right] \; and \; ACH(hr^{-1}) = \left[\frac{V}{Q}\right]^{-1}$$

D_t	Time elapsed (hr)
V	Volume of space (m^3)
Q	Flow rate of air through room (m^3/hr)
$C_{initial}$	Initial CO concentration (ppm)
C_{ending}	Ending CO concentration (ppm)
ACH	Air exchange per hour (hr^{-1})

No significant difference in the ventilation quality calculation was seen by excluding monitors located under the roof apex at either end of the model kitchen, indicates that there was no CO vertical stratification. The pollutant was thus assumed to be well-mixed in the space. Whole-kitchen average air exchanges are shown below in Figure 3.2.



CV: Two windows open, diagonally across kitchen; **O**: All windows and door open; **C**: All windows and doors sealed closed: **E**: Eaves under roof open: **3W**: One side of kitchen open: **2/3W**: All walls at 2/3 original height; **DEO**: Door and eaves under roof open: **DONE**: Door open, eaves sealed closed: **NO**: No other outlets: **T**: Thatched roofing instead of corrugated metal: **NF**: Fans off: **LF**: Fans on low; **HF**: Fans on high; **W**: wet fuel

Figure 3.2: Average air exchanges for each of the structural configurations. Calculations were based on the CO removal from the test kitchen as monitored by the field CO monitors.

As shown above, there is a significant difference in the air exchange rates between the cross ventilation (CV) scheme with any kind of fan speed and the rest of the configurations, venting 1.6-1.75 times more per hour than the completely closed, low fan (C_NO_LF) setup. A similar result was found in Grabow et al. 2013 when one window above the cookstove and the test kitchen door was open (increasing the air exchanges per hour from 3.2 ± 1.3 hr^{-1} to 12 ± 1.2 hr^{-1} in a 24.6 m^3 test kitchen). While it is not possible to control the wind in a real world setting, recommendations for installing windows in the prevailing wet and direction, and opposing corners, is recommended.

3.3.2 First –Order Decay Rates

While no modeling was conducted as part of this investigation, the number of monitors placed around the kitchen space made it possible to calculate fairly accurate decay constants for future modeling endeavors. Using $PM_{2.5}$ and CO as "tracers", the first-order decay rates were calculated for individual trials and then averaged per structural configuration (see Table 3.4 and Table 3.5 below). The time intervals used for the decay rate constant calculations are 0.75 fraction complete to end of trial for $PM_{2.5}$ and 0.68 fraction complete to end of trial for CO. The mean decay rate uncertainty is reported to one standard deviation.

Table 3.4. Mean $PM_{2.5}$ Decay Rate Constants by Structural Configuration.

	CV				*O*	*C*		*E*	*3W*	*2/3W*
	NO_NF	*NO_HF*	*DONE_HF*	*DONE_LF*	*DONE_LF*	*NO_LF*	*T_NO_LF*	*NO_LF*	*DEO_LF*	*DEO_LF*
ACH (hr^{-1})	3 ± 1	6 ± 1	6 ± 1	6 ± 1	3 ± 1	4 ± 1	4 ± 1	2 ± 1	2 ± 1	2 ± 1
Mean $PM_{2.5}$ Decay Rate (hr^{-1})	-0.12 ± 0.02	-0.15 ± 0.01	-0.15 ± 0.01	-0.14 ± 0.02	-0.12 ± 0.02	-0.12 ± 0.03	-0.11 ± 0.01	-0.12 ± 0.02	-0.13 ± 0.01	-0.15 ±0.01
Range (hr^{-1})	0.07	0.01	0.03	0.04	0.05	0.07	0.02	0.04	0.01	0.03
Min (hr^{-1})	-0.16	-0.15	-0.17	-0.16	-0.14	-0.17	-0.12	-0.15	-0.14	-0.16
Max (hr^{-1})	-0.1	-0.14	-0.14	-0.12	-0.09	-0.1	-0.11	-0.11	-0.12	-0.13
N (Trials)	13	3	4	3	9	8	5	3	3	3
N (Data points)	1563	330	490	390	1241	1079	670	430	380	320

CV: Two windows open, diagonally across kitchen; **O**: All windows and door open; **C**: All windows and doors sealed closed: **E**: Eaves under roof open: **3W**: One side of kitchen open: **2/3W**: All walls at 2/3 original height; **DEO**: Door and eaves under roof open: **DONE**: Door open, eaves sealed closed: **NO**: No other outlets: **T**: Thatched roofing instead of corrugated metal: **NF**: Fans off: **LF**: Fans on low; **HF**: Fans on high; **TSF**: Three-stone fire; **TSF(W)**: Three-stone fire, wet wood; **EF**: Envirofit G3300 Cook Stove; **EF(D)**: Envirofit Cook Stove place next to door; **EF(O)**: Envirofit Cook Stove placed in corner opposite original position; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt; **ST(W)**: StoveTec Cook Stove, wet wood

Table 3.5. Mean CO Decay Constants by Structural Configuration.

	CV				*O*	*C*		*E*	*3W*	*2/3W*
	NO_NF	*NO_HF*	*DONE_HF*	*DONE_LF*	*DONE_LF*	*NO_LF*	*T_NO_LF*	*NO_LF*	*DEO_LF*	*DEO_LF*
ACH (hr^{-1})	3 ± 1	6 ± 1	6 ± 1	6 ± 1	3 ± 1	4 ± 1	4 ± 1	2 ± 1	2 ± 1	2 ± 1
Mean CO Decay Rate (hr^{-1})	-0.04 ± 0.01	-0.10 ± 0.00	-0.10 ± 0.00	-0.10 ± 0.01	-0.04 ± 0.00	-0.05 ±0.01	-0.06 ± 0.00	-0.02 ±0.01	-0.02 ±0.01	-0.03 ±0.01
Range (hr^{-1})	0.06	0.003	0.01	0.03	0.03	0.14	0.02	0.02	0.03	0.03
Min (hr^{-1})	-0.07	-0.10	-0.11	-0.11	-0.06	-0.13	-0.07	-0.03	-0.04	-0.04
Max (hr^{-1})	-0.01	-0.1	-0.01	-0.08	-0.02	0.01	-0.06	-0.004	-0.004	-0.01
N (Trials)	13	3	4	3	9	8	5	3	3	3
N (Data points)	1718	246	396	343	1256	1088	680	432	384	336

CV: Two windows open, diagonally across kitchen; **O**: All windows and door open; **C**: All windows and doors sealed closed: **E**: Eaves under roof open: **3W**: One side of kitchen open: **2/3W**: All walls at 2/3 original height; **DEO**: Door and eaves under roof open: **DONE**: Door open, eaves sealed closed: **NO**: No other outlets: **T**: Thatched roofing instead of corrugated metal: **NF**: Fans off: **LF**: Fans on low; **HF**: Fans on high; **TSF**: Three-stone fire; **TSF(W)**: Three-stone fire, wet wood; **EF**: Envirofit G3300 Cook Stove; **EF(D)**: Envirofit Cook Stove place next to door; **EF(O)**: Envirofit Cook Stove placed in corner opposite original position; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt; **ST(W)**: StoveTec Cook Stove, wet wood

4 Discussion

Ventilation, like cookstove adoption, is dependent on social factors outside of organizations' control. The conclusions drawn from Kitchen 2.0 may not apply globally, or even regionally. It is the author's opinion that any intervention should be chosen based on a number of considerations including cost, maintenance, and most importantly, cultural acceptability.

4.1 CCT Observations

In review, the Controlled Cooking Test (CCT) is a cookstove testing protocol similar to the Water Boiling Test (WBT) in that it can be used to determine cookstove efficiency, but it uses a set meal instead of boiling and simmering water. This is meant to be more representative of real-world situations: how the cookstove in question would perform under more real-world conditions (the efficacy of a cookstove rather than just efficiency). However, it does have some drawbacks. A "meal" is not defined by the CCT, meaning the results from any cookstove test could vary significantly between cultures. Fortunately, rice is relatively universal staple, so the Kitchen 2.0 results should be applicable in most situations. Another drawback is additional data variability, because the focus of the test is to complete a cooking task. Factors considered in the WBT such as water temperature (an indicator for different cooking power levels) are not measured in the CCT. For Kitchen 2.0, even though the conditions were essentially the same trial to trial, using the CCT with different cooks very likely contributed variability from trial to trial. Additional repetitions of each configuration are needed to confirm the mean values presented in this work; this is discussed further in Section 4.2.

4.1.1 Anecdotes from Kitchen 2.0

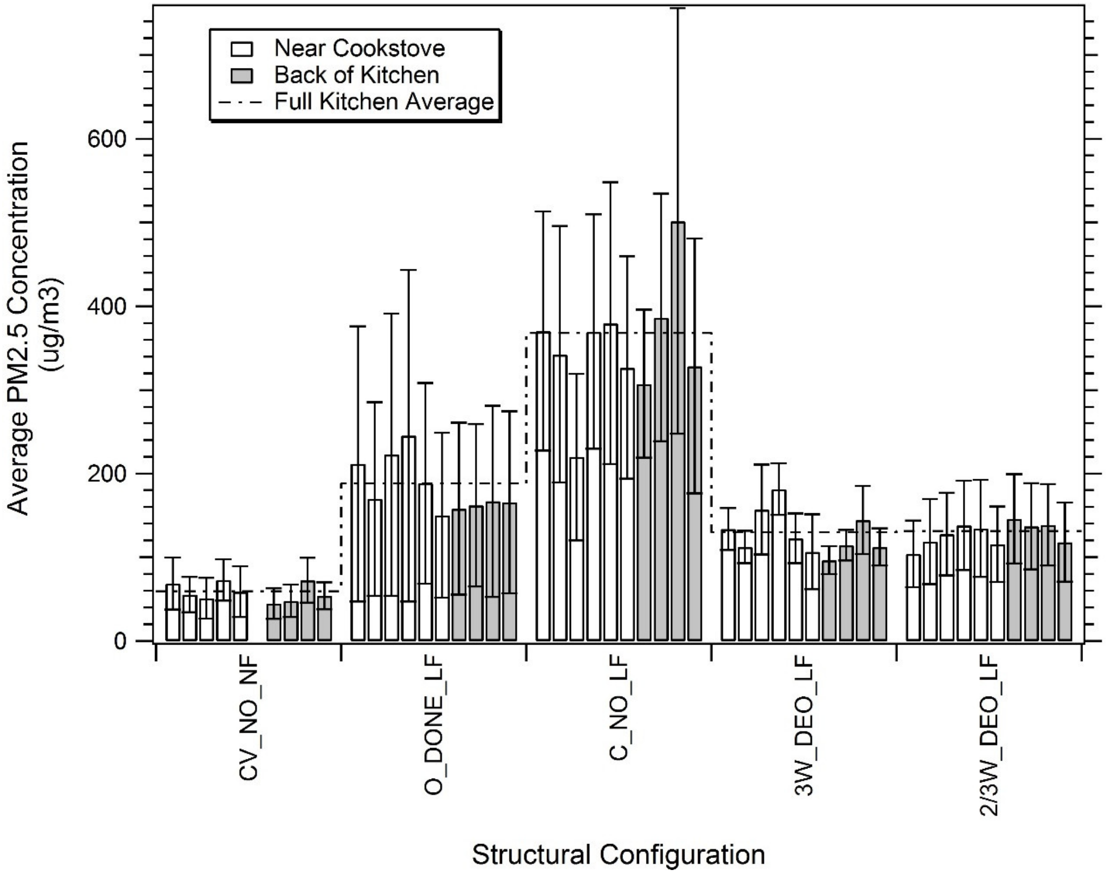
The three-stone cookstove required nearly constant attention from the "cook"; two attendants were required for the three-stone fire, wet fuel trials. Two attempted wet fuel test with the second cookstove tested, the StoveTec GreenFire cookstove, failed (water never reached a boil). These results were not included in the results above because both CCT tests were never completed; the main wood pieces would not light. For all other trials, the StoveTec was easier to light and to maintain. The "cooks" (members of the research team) noticed that fuel burned best in the StoveTec and Environfit cookstoves when the ignited ends were kept between mid-way and two thirds of the way into the combustion chamber (since the Kitchen 2.0 testing period, Aprovecho, the StoveTec manufacturer, has added a grill in the back of the combustion chamber to prevent users from pushing the fuel too far back). The Envirofit cookstove seemed to consume more fuel than the StoveTec cookstove, an observation which the data collection confirmed (see Table 3.1). For all cookstoves, the smaller fuel pieces burned more efficiently (less smoky, easier to ignite), but required more attention as they burned faster.

The cooking experience itself was humbling, and created empathy for the billions who endure poor indoor air quality on a daily basis. Large amounts of smoke were released at the beginning of the cooking tests before the wood pieces caught fire. Even more smoke was released when the fire was extinguished; as a safety precaution, the researchers always left the kitchen and clean room to allow the pollution to vacate the structures before reentering. In general, the completely sealed (C_NO_LF) cooking tests were despised. CO levels rose above 100 ppm at the cook's level, and the amount of particulate matter in the air caused eye and respiratory irritation for all occupants in the test kitchen. The air quality was visibly better with any ventilation and the physical effects from short-term HAP exposure much less. For safety during future research, it is recommended that a way be found to conduct the cooking outside of the kitchen or rock dust respirators be used instead.

Figure 4.1. Mollie Ruth in action during a three-stone fire trial. Photo credit: author.

4.2 Concentration

Although conditions and methodology were nearly identical from trial to trial (for a given configuration), post-data collection showed a surprising amount of variability in the HAP concentrations (illustrated in Figure 4.2 below). Factors like fuel heterogeneity and seemingly insignificant differences in cooking styles likely affected the amount of emissions generated during each trial, which dictated the concentrations of HAP measured in the model kitchen. Uncertainty (one standard deviation) ranged from 23% to 82% of the room average concentration of $PM_{2.5}$, but was much higher at individual monitor locations (one standard deviation range: 2% to 160% of average $PM_{2.5}$ concentration per structural configuration). A similar amount of variation was seen in the CO data. This amount of variability is commonly seen in field-collected data, implying that the Kitchen 2.0 results more accurately reflect real world conditions than more controlled laboratory experiments; an underlining objective of Kitchen 2.0. Unfortunately, the variability may have obscured the true effect of ventilation on HAP in a kitchen. Many more replications for each structural configuration and the use of a more homogeneous fuel source are recommended for future work.



CV: Two windows open, diagonally across kitchen; **O**: All windows and door open; **C**: All windows and doors sealed closed: **E**: Eaves under roof open: **3W**: One side of kitchen open: **2/3W**: All walls at 2/3 original height; **DEO**: Door and eaves under roof open: **DONE**: Door open, eaves sealed closed: **NO**: No other outlets: **T**: Thatched roofing instead of corrugated metal: **NF**: Fans off: **LF**: Fans on low; **HF**: Fans on high

Figure 4.2: Comparison of front of the room (unfilled bars) to back of the room averages (grey bars) for PM2.5. Each bar represents the arithmetic mean of the geometric means of the data per trial for one $PM_{2.5}$ monitor (variation between trials was assumed normal) for the Envirofit cookstove. The uncertainty bars represent one standard deviation of the variance between individual trials. No wet fuel results are depicted here.

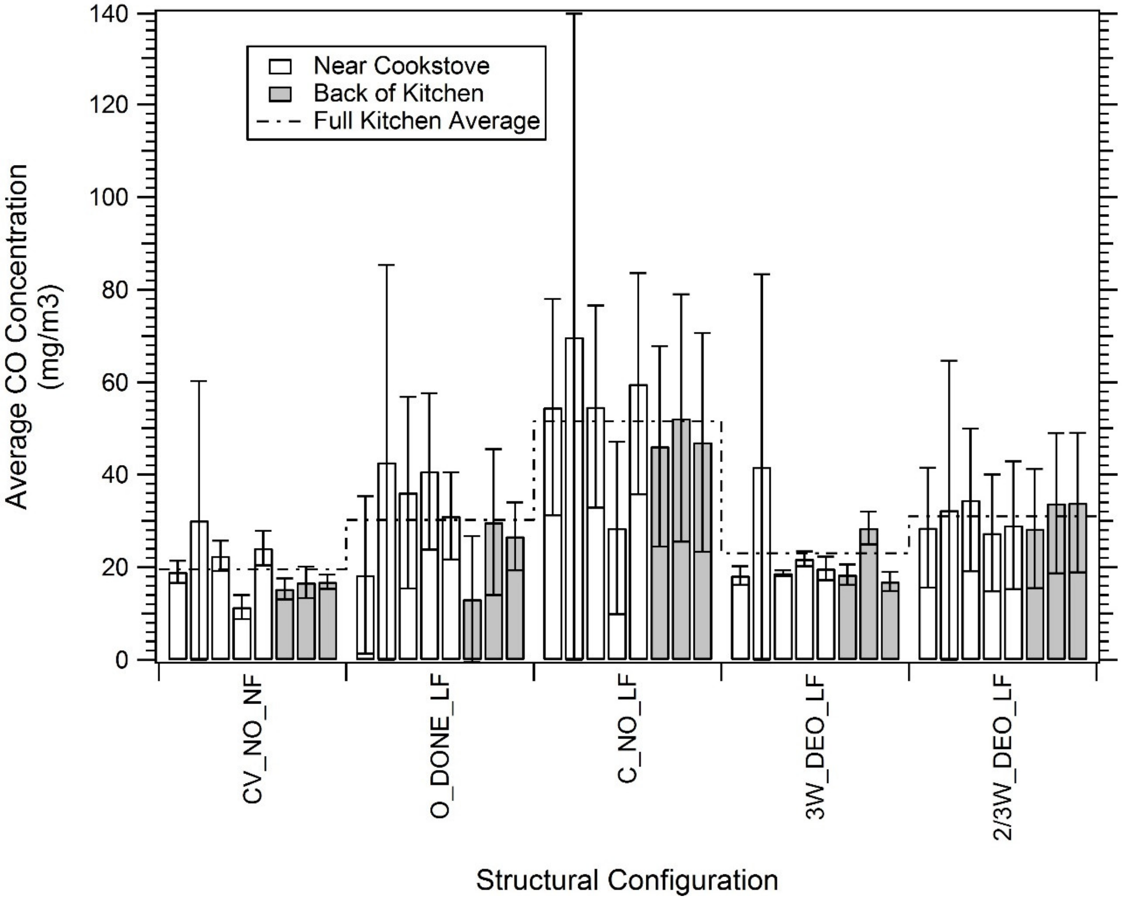


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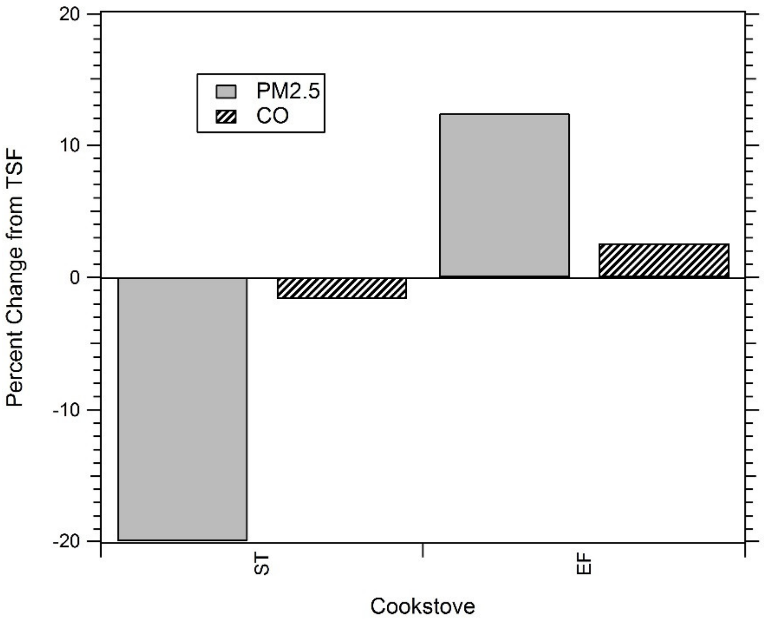
Figure 4.3: Variation in carbon monoxide concentration by monitor: unfilled bars near the cookstove and grey bars to back of the room. Each bar represents the arithmetic mean of the full trial averages one CO monitor (variation between trials was assumed normal) for the Envirofit cookstove. The uncertainty bars represent one standard deviation of the variance between individual trials. No wet fuel results are depicted here.

4.3 Ventilation

A combination of ventilation and improved cookstoves was sufficient to reduce concentration by the recommended 50-90% on average, except in the completely sealed configuration (see Table 3.2 and Table 3.3 in Section 3.2.1 above for reference). Under these circumstances, the use of an improved cookstove over the three-stone fire did not result in any change in HAP. In fact, in some instances the concentration of CO and $PM_{2.5}$ was higher (see Figure 4.4 below for reference). Therefore, alternative interventions should be considered in these cases, such as a chimney or hood system, or developing some other kind of socially acceptable ventilation system.



TSF: Three-stone fire; **EF**: Envirofit G3300 Cook Stove; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt;

Figure 4.4: Percent change in full kitchen $PM_{2.5}$ and CO concentrations by cookstove under completely sealed conditions (C_NO_LF). The results from the three stone cookstove, completely sealed (CV_NO_LF) combination were used as a baseline for the comparison.

One important conclusion drawn from Kitchen 2.0 is that not all ventilation is created equal. Intuitively, if opening a window or the door of a space improves the IAQ a little, opening more windows and doors should result in an even greater improvement. This was not the case in Kitchen 2.0. The air exchanges per hour (Figure 3.2) when all of the windows and doors were open

(O_DONE_LF) was similar to that of the completely sealed (C_NO_LF) trials (3.0±0.8 hr^{-1} and 3.9±0.5 hr^{-1}, respectively). The highest air exchange rate achieved was 6.3±0.8 hr^{-1} when only two windows were open (CV_NO_HF). Figure 4.2 and Figure 4.3 further illustrates this conclusion. Although no structural configuration significantly deceased the average $PM_{2.5}$ concentration, the two-window "cross ventilation" (CV_NO_LF) set up is visibly superior to the other configurations tested. It should be noted that the lack of IAQ improvement in the all open (O_DONE_LF) trials may be due to mixing and reentry of HAP from the clean room. This phenomenon should be investigated in future studies.

4.3.1 Comparison of Air Exchanges to Decay Rates

A least squares regression analysis showed no correlation between the number of air exchanges per hour and the $PM_{2.5}$ first-order decay rate for all of the structural configurations considered in this investigation. This suggests that ventilation is not the predominant removal force for $PM_{2.5}$; other phenomena such as deposition may have a greater effect. On the other hand, the number of air exchange rates per hour and the first-order decay rate for CO were well-correlated to a linear fit. Therefore, ventilation may be one of the principal, if not the principal, removal forces for the contaminant. See Figure 4.5 below.

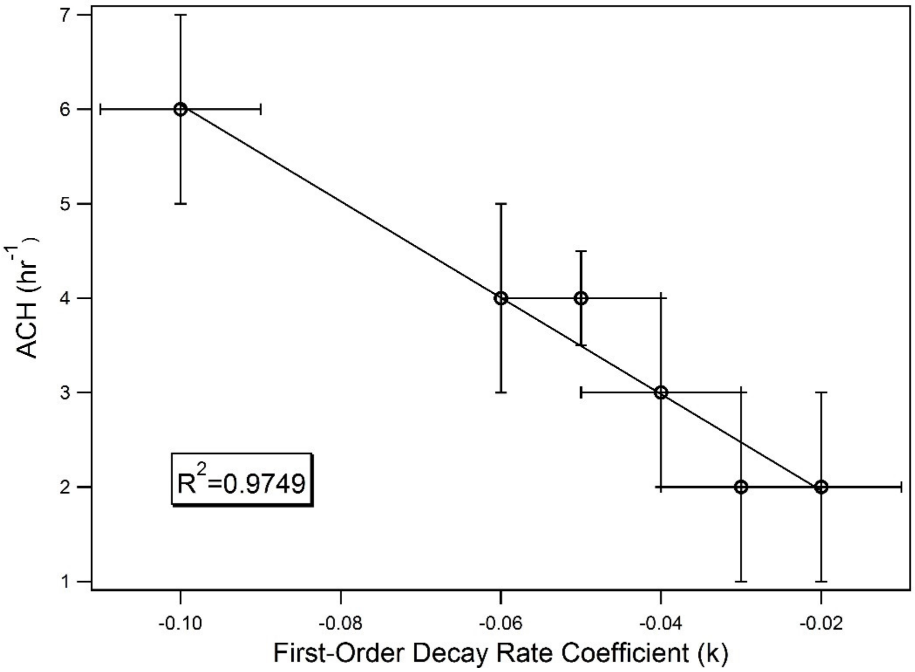


Figure 4.5: Correlation between CO decay rate and the air exchange rates tested in Kitchen 2.0. The error bars represent one standard deviation from the cookstove/structural configuration mean.

4.4 Exposure

Improvement in human health by reducing exposure to HAP is one of the primary motives behind the development and distribution of improved cookstoves, as well as for this study. The WHO air quality guidelines (AQG) recommend a maximum exposure to $PM_{2.5}$ and CO are 25 $\mu g/m^3$ and 7 mg/m^3, respectively, over a 24-hour period (WHO, 2014). These standards are compared with 24-hour exposure estimated from the Kitchen 2.0 results in Figure 4.6 and Figure 4.7 below. The Kitchen 2.0 estimates were calculated from the whole-kitchen, geometric mean concentrations of $PM_{2.5}$ and CO for a complete cooking event, and are based on the assumption that the cookstove will be lit only for four hours per day. Other sources of HAP exposure, such as environmental HAP, were not included in the estimates since only indoor HAP exposure is of interest here. Therefore, the Kitchen 2.0 results are likely to underestimate the total daily exposures to CO and $PM_{2.5}$.

Most of the cookstove and structural combinations considered in Kitchen 2.0 met or were below the WHO 24-hour exposure limit for both $PM_{2.5}$ and CO.

The two cases that exceeded the 24-hour $PM_{2.5}$ guideline were the wet fuel and the completely sealed combinations. Excess moisture in fuel has a smothering effect, so the fuel only burns poorly at best. HAP in a completely sealed space has little to no outlet, so pollutant concentrations simply build as the cooking event progresses. Occupants living and working in both of these situations are at high risk for developing respiratory and cardiovascular disease.

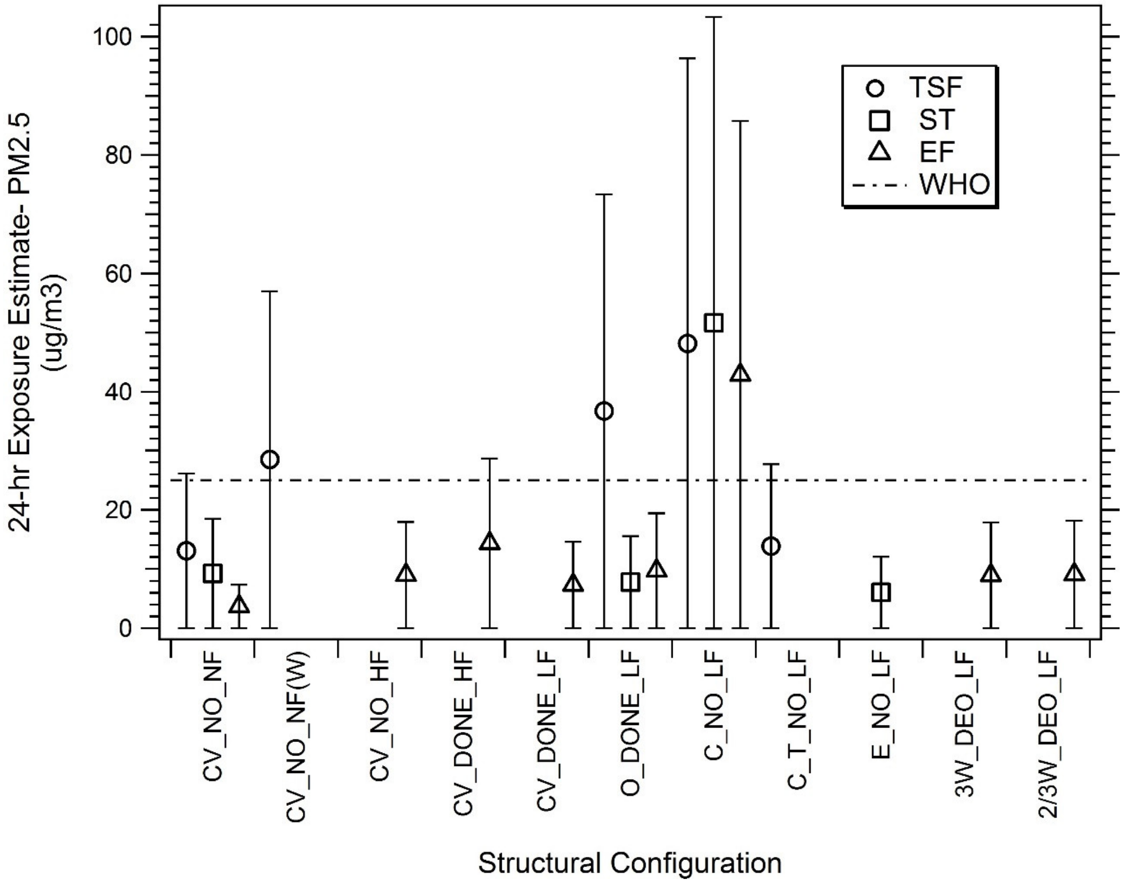


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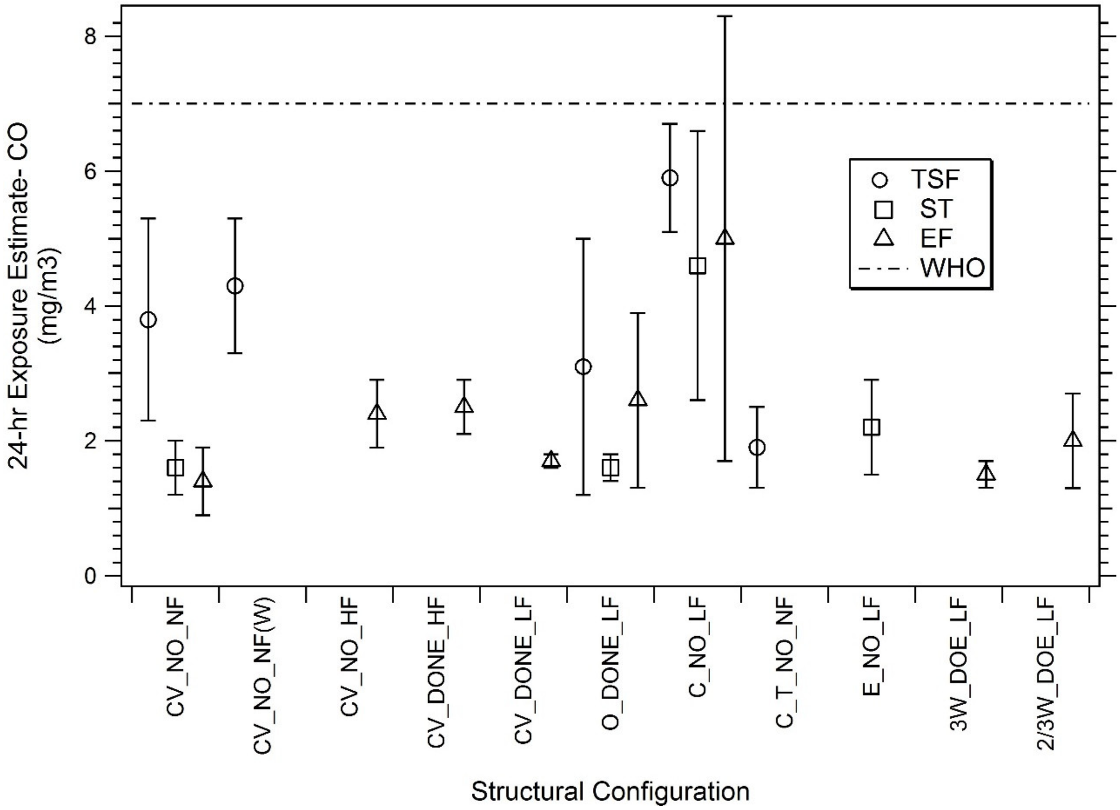
Figure 4.6: 24-hour average exposures to $PM_{2.5}$ by cookstove and structural configuration. Each marker represents the mean of the trials per cookstove/structural configuration, and the errors bars represent one standard deviation from the mean.



CV: Two windows open, diagonally across kitchen; **O**: All windows and door open; **C**: All windows and doors sealed closed: **E**: Eaves under roof open: **3W**: One side of kitchen open: **2/3W**: All walls at 2/3 original height; **DEO**: Door and eaves under roof open: **DONE**: Door open, eaves sealed closed: **NO**: No other outlets: **T**: Thatched roofing instead of corrugated metal: **NF**: Fans off: **LF**: Fans on low; **HF**: Fans on high; **W**: wet fuel

Figure 4.7: The calculated 24 hour exposure to CO by cookstove and structural configuration. No cookstoves in a completely sealed environment met the WHO air quality guideline (AQG) of 7 mg/m^3. The wet fuel trial TSF(W) also exceeded the AQG. Error bars represent one standard deviation from the mean.

5 Conclusions

The worldwide use of biomass and other unrefined fuel sources to meet daily household energy needs has potentially large negative ramifications for human health, the environment, and the global climate. Research and engineering in this field of interest has expanded exponentially in the last decade, with organizations ranging from community-level action committees to international aid organizations. Thousands of improved combustion cookstove options are available now on the market, but many of these cookstoves do not achieve a similar reduction in emissions (directly linked to human exposure) in the field as they do in laboratory testing. In an effort to merge controlled laboratory and real world conditions, the Kitchen 2.0 project examined the combined effect of structural differences and cookstove technology on HAP using the Controlled Cooking Test (CCT) under controlled ventilation conditions. Two household air pollutants particulate matter ($PM_{2.5}$) and carbon monoxide (CO) were monitored in real-time at 15 locations in a model kitchen to assess the spatial variation in pollutant concentrations and to calculate the average concentrations of HAP in the space.

Based on the project results, the greatest improvement in air quality can be achieved through a combination of a cross-kitchen air flow (CV_NO_HF in the text) and a cookstove with an improved combustion chamber. This is likely due to the significant increase in the air exchange rate for the structural configuration, although there are no correlation between the removal of $PM_{2.5}$, calculated as a first order decay rate, and the number of air exchanges per hour. Ventilation did play a large role in maintaining human exposure level below the WHO 24-hour AQG except when the fuel was wet.

Additional research is needed. First, the Aprovecho Stove Tec cookstove failed two CCT trials when the fuel was wet. The author is unsure if the failures were due to user error or a limitation of the cookstove; this should be investigated further since cured wood is not guaranteed outside of the laboratory. Second, it was assumed for this work that there was no pollutant reentry, but due to the proximity of the clean room walls to the model kitchen, this is unlikely. The amount of HAP reentering into the model kitchen from the clean room should be quantified in future studies. Finally, the concentrations of both pollutants varied greatly from trial to trial, and the number of replications possible during Kitchen 2.0 for each structural/cookstove combination was time constrained. Additional trials are needed to quantify definitively the effect that ventilation has on indoor air quality.

5.1 Recommendations to Key Stakeholders

A few closing remarks for four critical stakeholder groups from the author:

- Fellow researchers: The improved cookstoves did not perform as well as expected, particularly when there is little or no air movement around the cooktove and wet fuel is being burned. Real-world adaptations for the laboratory-based Water Boiling Test should be developed so that cookstove ratings reflect in-kitchen performance.

- Cookstove development agencies: The Water Boiling Test is a necessary evil. It allows for the comparison of hundreds of technological solutions under highly replicable conditions. However, more emphasis needs to be placed on the other two testing protocols: the Controlled Cooking Test and the Kitchen Performance Test. Without obtaining data using all three protocols, the cookstove performance ratings will be meaningless.

- Aid organizations: To reiterate the IWA 11: 2012 documentation, selecting a cookstove should not be based solely on the tiered performance rating. Cost, cultural acceptability, and maintenance should also play an important role in the decision. As this work states, ventilation can also improve indoor air quality. One or a combination of both should be considered prior to implementation, depending on local customs.
- Community members: Particulate matter or “smoke” is a visible nuisance. It causes eye and lung irritation, and stains your kitchen walls. Installing two windows in your kitchen so that the wind blows through and out of your kitchen will improve your family’s health and keep your kitchen cleaner.

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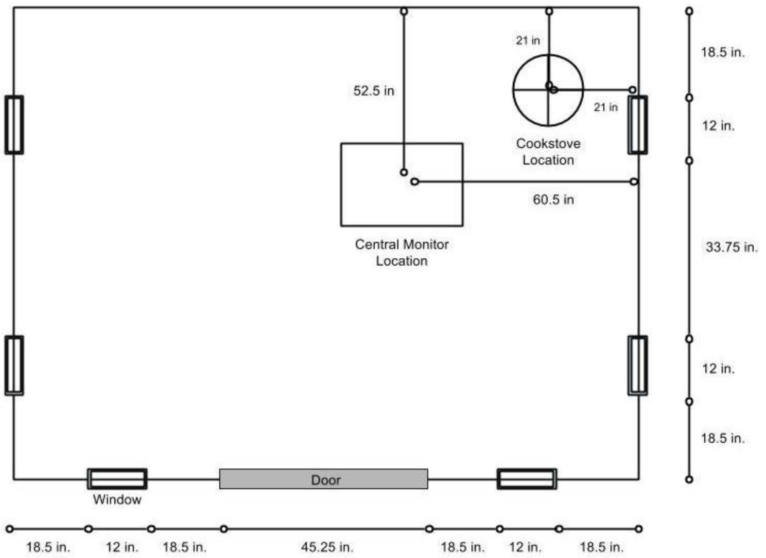
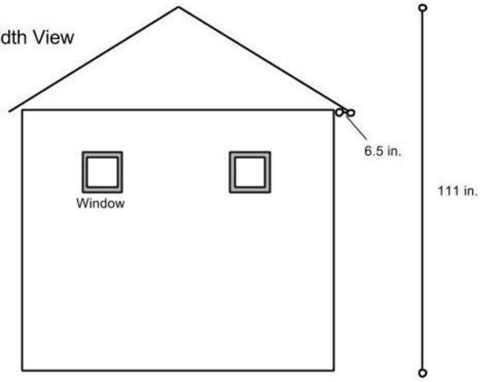
APPENDIX A: Design Drawings

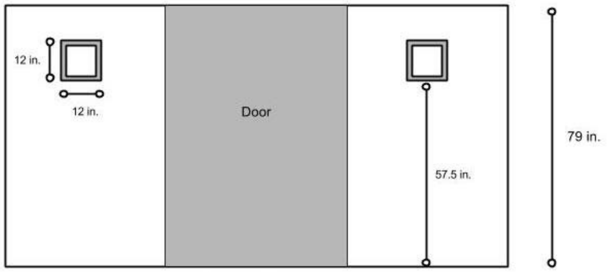
Modular Kitchen Dimensions



Plan View

Width View





Length View

APPENDIX B: Full Trial Results- $PM_{2.5}$

	CV_NO_NF				CV_NO_HF	CV_DONE_HF	CV_DONE_LF
	TSF (T1-4)	*ST (T5-7)*	*EF (T8-10)*	*TSF(W) (T47-49)*	*EF (T11-13)*	*EF (T14-16)*	*EF (T19-20)*
Full Trial Average Time (hr)	0.8	0.7	0.8	0.9	0.7	0.7	0.8
Full Kitchen Mean (μg/m^3)	177.8	136.6	59.2	364.2	178.0	149.4	152.6
Full Kitchen Standard Dev.	50.0	94.8	19.2	86.2	29.9	93.0	84.3
Time to Cook (hr)	0.4	0.4	0.4	0.4	0.3	0.4	0.3
Hourly Exposure (μg/hr*m^3)	78.3	55.3	22.0	171.0	53.7	85.9	43.8
Hourly Exposure Standard Dev. (μg/hr*m^3)	11.7	28.1	3.5	85.8	12.4	63.1	12.7
24-hr Exposure (WHO method; μg/hr*m^3)	13.1	9.2	3.7	28.5	9.0	14.3	7.3
24-hr Exposure Standard Dev. (μg/hr*m^3)	1.9	4.7	0.6	14.3	2.1	10.5	2.1
Kurtosis	9.5	15.8	47.5	4.5	13.6	21.3	11.5
Skewness	2.4	3.0	6.0	1.8	3.1	3.6	2.6
Range (μg/m^3)	3841.3	2105.5	2608.1	4002.8	3089.2	3702.7	2845.7
Minimum (μg/m^3)	0.6	0.9	0.6	0.6	1.1	1.0	1.8
Maximum (μg/m^3)	3841.9	2106.4	2608.7	4003.3	3090.3	3703.7	2847.6
Measurement Count	1394	864	954	1220	920	1370	1090

CV: Two windows open, diagonally across kitchen; **DONE**: Door open, eaves sealed closed; **NO**: No other outlets; **NF**: Fans off; **LF**: Fans on low; **HF**: Fans on high; **TSF**: Three-stone fire; **TSF(W)**: Three-stone fire, wet wood; **EF**: Envirofit G3300 Cook Stove; **EF(D)**: Envirofit Cook Stove place next to door; **EF(O)**: Envirofit Cook Stove placed in corner opposite original position; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt; **ST(W)**: StoveTec Cook Stove, wet wood

	O_DONE_LF			**C_NO_LF**			**E_NO_LF**	**3W_DEO_LF**	**2/3W_DEO_LF**	**CV_T_NO_NF**
	TSF (T21, 26, 29)	*ST (T22, 25, 28)*	*EF (T23, 24, 27)*	*EF (T30, 33, 35)*	*ST (T31, 34, 36)*	*TSF (T32, 37)*	*ST (T38-40)*	*EF (T41-43)*	*EF (T44-46)*	*TSF (T50-54)*
Full Trial Average Time (hr)	1.0	0.8	0.8	0.8	0.8	0.9	0.9	0.8	0.7	0.8
Full Kitchen Mean (μg/m^3)	335.3	101.3	188.1	368.0	309.5	291.1	59.3	129.8	131.1	183.9
Full Kitchen Standard Dev.	405.7	45.5	139.7	149.2	312.0	14.4	30.6	43.1	52.6	115.0
Time to Cook (hr)	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.3	0.4
Hourly Exposure (μg/hr*m^3)	220.0	46.5	58.1	257.3	309.9	289.2	36.3	53.5	54.5	83.2
Hourly Exposure Standard Dev. (μg/hr*m^3)	256.3	7.3	37.2	88.4	373.6	29.7	27.5	29.2	25.5	51.3
24-hr Exposure (WHO method; μg/hr*m^3)	36.7	7.8	9.7	42.9	51.7	48.2	6.0	8.9	9.1	13.9
24-hr Exposure Standard Dev. (μg/hr*m^3)	42.7	1.2	6.2	14.7	62.3	4.9	4.6	4.9	4.3	8.5
Kurtosis	3.1	56.6	13.1	1.8	1.3	3.2	40.3	33.2	4.1	14.5
Skewness	1.6	6.1	3.1	1.6	1.5	1.7	5.4	4.9	1.5	3.1
Range (μg/m^3)	3628.0	3185.8	3530.8	4595.3	4602.9	4397.4	3586.4	3950.9	1310.3	3841.3
Minimum (μg/m^3)	1.7	8.9	1.4	1.3	1.4	11.5	0.9	0.9	1.2	0.6
Maximum (μg/m^3)	3629.7	3194.7	3532.2	4596.6	4604.4	4409.0	3587.3	3951.8	1311.5	3841.9
Measurement Count	1350	1080	1100	1139	1070	839	1220	1080	931	3212

E: Eaves under roof open; **O**: All windows and door open; **C**: All windows and doors sealed closed; **3W**: One side of kitchen open; **2/3W**: All walls at 2/3 original height; **DEO**: Door and eaves under roof open; **DONE**: Door open, eaves sealed closed; **NO**: No other outlets; **T**: Thatched roofing instead of corrugated metal; **NF**: Fans off; **LF**: Fans on low; **HF**: Fans on high; **TSF**: Three-stone fire; **TSF(W)**: Three-stone fire, wet wood; **EF**: Envirofit G3300 Cook Stove; **EF(D)**: Envirofit Cook Stove place next to door; **EF(O)**: Envirofit Cook Stove placed in corner opposite original position; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt; **ST(W)**: StoveTec Cook Stove, wet wood

APPENDIX C: Full Trial Results- CO

	CV_NO_NF				CV_NO_HF	CV_DONE_HF	CV_DONE_LF
	TSF (T1-4)	*ST (T5-7)*	*EF (T8-10)*	*TSF(W) (T47-49)*	*EF (T11-13)*	*EF (T14-16)*	*EF (T19-20)*
Full Trial Average Time (hr)	0.8	0.7	0.8	0.9	0.7	0.7	0.8
Full Kitchen Mean (mg/m^3)	36.7	22.7	19.5	48.7	44.8	29.6	23.0
Full Kitchen Standard Dev. (mg/m^3)	8.9	2.5	2.1	17.3	3.5	6.3	6.7
Time to Cook (hr)	0.4	0.4	0.4	0.4	0.3	0.4	0.3
Hourly Exposure (mg/hr*m^3)	22.9	9.5	8.6	25.5	14.2	14.7	9.9
Hourly Exposure Standard Dev. (mg/hr*m^3)	9.1	2.6	2.8	6.3	3.2	2.6	1.7
24-hr Exposure (mg/hr*m^3)	3.8	1.6	1.4	4.3	2.4	2.5	1.7
24-hr Standard Dev. (mg/hr*m^3)	1.5	0.4	0.5	1.0	0.5	0.4	0.1
Kurtosis	-0.2	7.1	53.9	0.4	16.7	7.8	5.0
Skewness	0.0	1.8	4.4	0.6	3.0	1.7	1.8
Range (mg/m^3)	125.2	176.7	314.6	239.7	246.9	204.8	140.4
Minimum (mg/m^3)	12.7	9.6	7.3	23.3	0.4	0.0	1.1
Maximum (mg/m^3)	137.9	186.3	321.9	263.0	247.2	204.8	141.5
Measurement Count	1240	768	848	968	552	889	763

CV: Two windows open, diagonally across kitchen; **DONE**: Door open, eaves sealed closed; **NO**: No other outlets; **NF**: Fans off; **LF**: Fans on low; **HF**: Fans on high; **TSF**: Three-stone fire; **TSF(W)**: Three-stone fire, wet wood; **EF**: Envirofit G3300 Cook Stove; **EF(D)**: Envirofit Cook Stove place next to door; **EF(O)**: Envirofit Cook Stove placed in corner opposite original position; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt; **ST(W)**: StoveTec Cook Stove, wet wood

	O_DONE_LF			C_NO_LF			E_NO_LF	3W_DEO_LF	2/3W_DEO_LF	CV_T_NO_NF
	TSF (T21, 26, 29)	*ST (T22, 25, 28)*	*EF (T23, 24, 27)*	*EF (T30, 33, 35)*	*ST (T31, 34, 36)*	*TSF (T32, 37)*	*ST (T38-40)*	*EF (T41-43)*	*EF (T44-46)*	*TSF (T50-54)*
Full Trial Average Time (hr)	1.0	0.8	0.8	0.8	0.8	0.9	0.9	0.8	0.7	0.8
Full Kitchen Mean (mg/m^3)	28.6	19.4	30.2	71.5	51.6	57.1	30.6	23.0	31.0	27.1
Full Kitchen Standard Dev. (mg/m^3)	13.0	6.3	14.3	19.6	22.9	3.9	4.9	4.9	14.1	2.2
Time to Cook (hr)	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.3	0.4
Hourly Exposure (mg/hr*m^3)	18.3	9.8	15.5	29.8	27.5	35.4	13.0	9.2	12.1	11.3
Hourly Exposure Standard Dev. (mg/hr*m^3)	11.2	1.3	7.8	19.7	12.0	4.7	3.9	1.0	4.2	3.5
24-hr Exposure (mg/hr*m^3)	3.1	1.6	2.6	5.0	4.6	5.9	2.2	1.5	2.0	1.9
24-hr Standard Dev. (mg/hr*m^3)	1.9	0.2	1.3	3.3	2.0	0.8	0.7	0.2	0.7	0.6
Kurtosis	0.7	6.2	11.5	1.4	4.5	-1.3	0.6	3.0	1.3	3.2
Skewness	0.8	2.0	2.3	0.9	1.5	-0.4	0.5	1.2	0.7	1.0
Range (mg/m^3)	124.8	133.3	298.5	381.1	373.2	164.6	141.1	139.1	146.4	155.1
Minimum (mg/m^3)	12.9	12.5	11.0	7.1	11.3	19.2	15.9	22.2	18.8	0.0
Maximum (mg/m^3)	137.7	145.8	309.5	388.2	384.5	183.8	157.0	161.3	165.2	155.1
Measurement Count	1072	864	880	904	856	672	976	864	744	1520

E: Eaves under roof open; **O**: All windows and door open; **C**: All windows and doors sealed closed; **3W**: One side of kitchen open; **2/3W**: All walls at 2/3 original height; **DEO**: Door and eaves under roof open; **DONE**: Door open, eaves sealed closed; **NO**: No other outlets; **T**: Thatched roofing instead of corrugated metal; **NF**: Fans off; **LF**: Fans on low; **HF**: Fans on high; **TSF**: Three-stone fire; **TSF(W)**: Three-stone fire, wet wood; **EF**: Envirofit G3300 Cook Stove; **EF(D)**: Envirofit Cook Stove place next to door; **EF(O)**: Envirofit Cook Stove placed in corner opposite original position; **ST**: StoveTec GreenFire Combo 2 Door Biomass Cook Stove without Pot Skirt; **ST(W)**: StoveTec Cook Stove, wet wood