THESIS

TESTING METHODOLOGIES FOR BIOMASS COOK STOVES AND THEIR EFFECTS ON EMISSIONS

Submitted by

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April 27, 2009

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY

CHRISTIAN COLIN PER L'ORANGE ENTITLED *TESTING METHODOLOGIES FOR BIOMASS COOK*

STOVES AND THEIR EFFECTS ON EMISSIONS BE ACCEPTED AS FULFILLING IN PART

REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

TESTING METHODOLOGIES FOR BIOMASS COOK STOVES AND THEIR EFFECTS ON EMISSIONS

More than half the world's population relies on biomass fuels to provide the energy for their everyday cooking and heating needs. During the combustion of biomass fuels such as wood there is the potential for toxic emissions to be released having both health and environmental implications. The smoke and toxic gases released from biomass cook stoves have been found responsible for 2.6% of global illness and the death of more than two million children annually. More than 30 years of research has been conducted around the world attempting to design clean burning high efficiency stoves that are tested following different testing protocols.

Biomass combustion is a complex process making it difficult to accurately measure. To have confidence in the measured performance of a stove a robust testing protocol must be used. The performance of a biomass cook stove will be effected by its physical parameters and the test method used. Testing methodologies for biomass cook stoves have been explored theoretically and experimentally in the hope of isolating and correcting the sources of potential error and variation in the test. With an improved test procedure established it becomes possible to begin to explore the parameters affecting the performance of a stove and to better understand the emissions released during use.

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Summer 2009

ACKNOWLEDGEMENTS

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List of Abbreviations

ALA	-	American Lung Association
ALRI	-	Acute Lower Respiratory Infection
BIS	-	Bureau of Indian Standards
C_2H_4O	-	Acetaldehyde
CAA	-	Clean Air Act
CFK	-	Coburn-Forster-Kane Equation
CH_4	-	Methane
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
COHb	-	Carboxyhemoglobin
DNES	-	Department of Non-Conventional Energy Sources
EC	-	Elemental Carbon
EEGL	-	Emergency Exposure Guidance Level
EF	-	Emissions Factor
GWP	-	Global Warming Potential
H_2CO	-	Formaldehyde
HCN	-	Hydrogen Cyanide
HEPA	-	High Efficiency Particulate Air (Filter)
IAP	-	Indoor Air Pollution
ICRP	-	International Commission on Radiological Protection
IDLH	-	Immediately Dangerous to Life or Health
LOD	-	Limit of Detection
LOQ	-	Limit of Quantification
MC	-	Moisture Content
MCE	-	Modified Combustion Efficiency

NAAQS	-	National Ambient Air Quality Standards
NC	-	Net Carbon
NIOSH	-	National Institute for Occupational Safety and Health
NPIC	-	National Programme on Improved Chulhas
NRC	-	National Research Council
O_2	-	Oxygen
OSHA	-	Occupational Safety and Health Administration
OC	-	Organic Carbon
PIC	-	Products of Incomplete Combustion
PM	-	Particulate Matter
PM_{10}	-	Particulate Matter with a Diameter 10μm or Less
ppm	-	Parts Per Million
RH	-	Relative Humidity
TC	-	Thermocouple
VITA	-	Volunteers in Technical Assistance
WBT	-	Water Boil Test
WHO	-	World Health Organization

1.   Motivation

In a world of over six and half billion people more than half still cook and heat their homes the way their ancestors have for thousands of years. Biomass fuels such as wood, agricultural waste, animal dung, and charcoal is estimated to provide over 90% of energy in some rural regions of the world [1]. Although biomass fuels have the potential of supplying carbon neutral energy many of the stoves and heaters currently in use around the world are highly inefficient. Products of incomplete combustion (PIC) released from stoves in the form of toxic gaseous and airborne particles can lead to both environmental damage and life threatening air quality conditions.

International groups are working to design and disseminate clean burning, high efficiency cook stoves but despite the nearly 30 years of work a universal testing standard has yet to be adopted. Many of the standards and testing methodologies that are currently in use fail to control factors that can influence performance or rely on unreasonable correction factors. The test procedure used can affect the performance of a stove; if caution is not taken this can lead to inconsistent test results.

If a standard stove test protocol can be established it becomes possible to characterize performance and begin the process of designing better products. To develop a clean high efficiency cook stove it is necessary to understand what affects emissions and performance and how the testing protocol influences test results.

1.1. Indoor Air Pollution

Indoor air pollution (IAP) from sources such as biomass combustion has been shown to be a major contributor in the death of over two million children each year. Poor indoor air quality has been linked to acute lower respiratory infection (ALRI) [1] and the smoke released from wood combustion more than doubles the risk of children developing a respiratory illness [2]. Women and children are at the greatest risk of experiencing long term health complications from IAP from the extensive amount of time spent in close proximity to stoves during its use. It is not uncommon for women to spend 90% of the more than five hours of daily cooking within two meters of the stove [3]. Women who cook on biomass stoves are twice as likely to experience multiple still births as women using gas stoves [4]. Extensive research has been done on the effects of combustion aerosols on the body but the vast majority of research has focused on fossil fuel or tobacco combustion both of which differ significantly from wood smoke [5].

1.2. Global Impacts of Biomass Combustion

Despite the potential for clean energy most of the biomass stoves currently available perform very poorly. The low performance of biomass stoves has lead to deforestation and the release of greenhouse gases. 10% of annual deforestation is estimated to come from the gathering of wood for cooking [6]. Carbon dioxide (CO_2) is the most often discussed greenhouse gas but many of the other compounds from biomass combustion have a greater global warming potential (GWP) [6] [7]. The GWP is the ratio of global warming impact between one mole of a compound and one mole of CO_2 [6] [8]. The emissions released from biomass fuels are eventually converted to CO_2

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and reabsorbed by plants but they have a significant impact on the total GWP until that occurs.   The GWP of methane (CH_4) is 21 at release and will still be 3.2 times after 500 years [8]. Ahuja has shown that emissions from biomass cook stoves could be responsible for as much as 1-2% of global warming each year. Improving combustion efficiency could cut that number nearly in half [7].

1.3.   Traditional and Improved Cook Stoves

The stoves being used in rural communities around the world have remained nearly unchanged for centuries. Most traditional stoves have the same foundation, an open, uncontrolled fire. The most common stove in most areas of the world is the three stone fire, as seen in Figure 1-1. A three stone fire is built directly on the ground with a pot placed above the flames similar to a camp fire. The performance of a three stone fire is diminished by lack of air control and the amount of energy lost to the ground from conduction. "Improved" stoves attempt to control the combustion process and improve heat transfer to the pot reducing total fuel consumption and the emissions released [9].
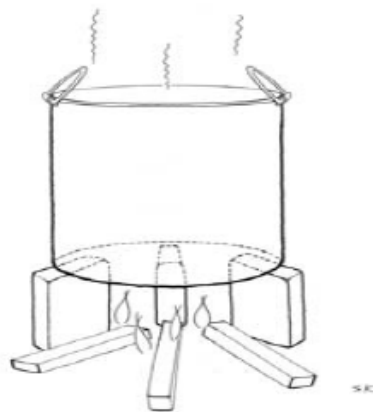
Figure 1-1: Three Stone Fire [10]

The factor which ultimately convinces an individual to switch to an improved stove depends on their location and how the stove is to be used. In many regions the aspiration for an improved stove is based on fuel economy. Fuel wood may be collected or purchased but all stove users want to minimize fuel consumption; either to save money or to save time collecting it. If fuel is easily and cheaply acquired the need for improved fuel economy becomes less crucial and the desire for an improved stove maybe based on perceived social status. The stove maybe purchased to reduced the need to clean the cook pots and the kitchen or simply because the stove is purchased. The ability to purchase a stove is often times seen as a sign of affluence. Designing improved cook stoves is typically done to improve health conditions or reduce deforestation but these factors alone do not sell a stove [11].

Several "improved" stoves were used during testing, such as the stove in Figure 1-2, but all had similar designs. All the stoves used had a fuel grate which held the fuel a 1-3 centimeters above the base of the stove. By raising the fuel off the bottom of the stove less heat is lost through conduction, coals & ash can break off the ends of the sticks, and air can flow around all sides of the fuel. Each of the stoves also had a pot support which held the cooking pot ~1 centimeter from the top of the stove. This pot support allowed exhaust gases to flow around the pot. The stoves used were ~30 centimeters in height and ~10 centimeters inner diameter. A cross-sectional view and flow path of one of the stoves used can be seen in Figure 1-3.
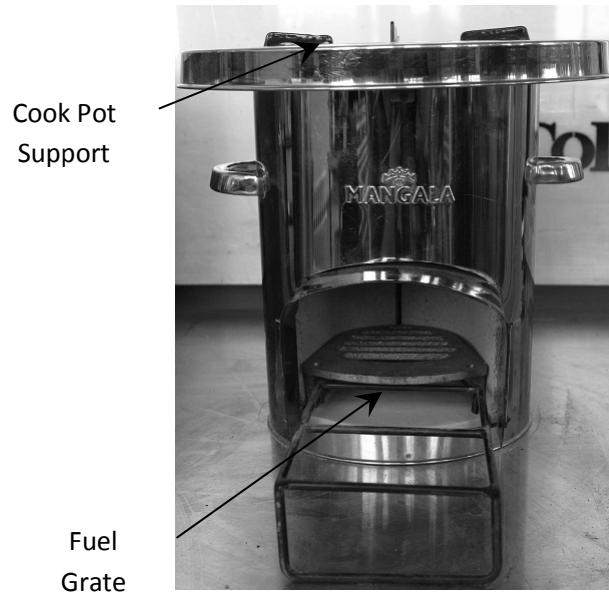
Figure 1-2: Improved Wood Cook Stove
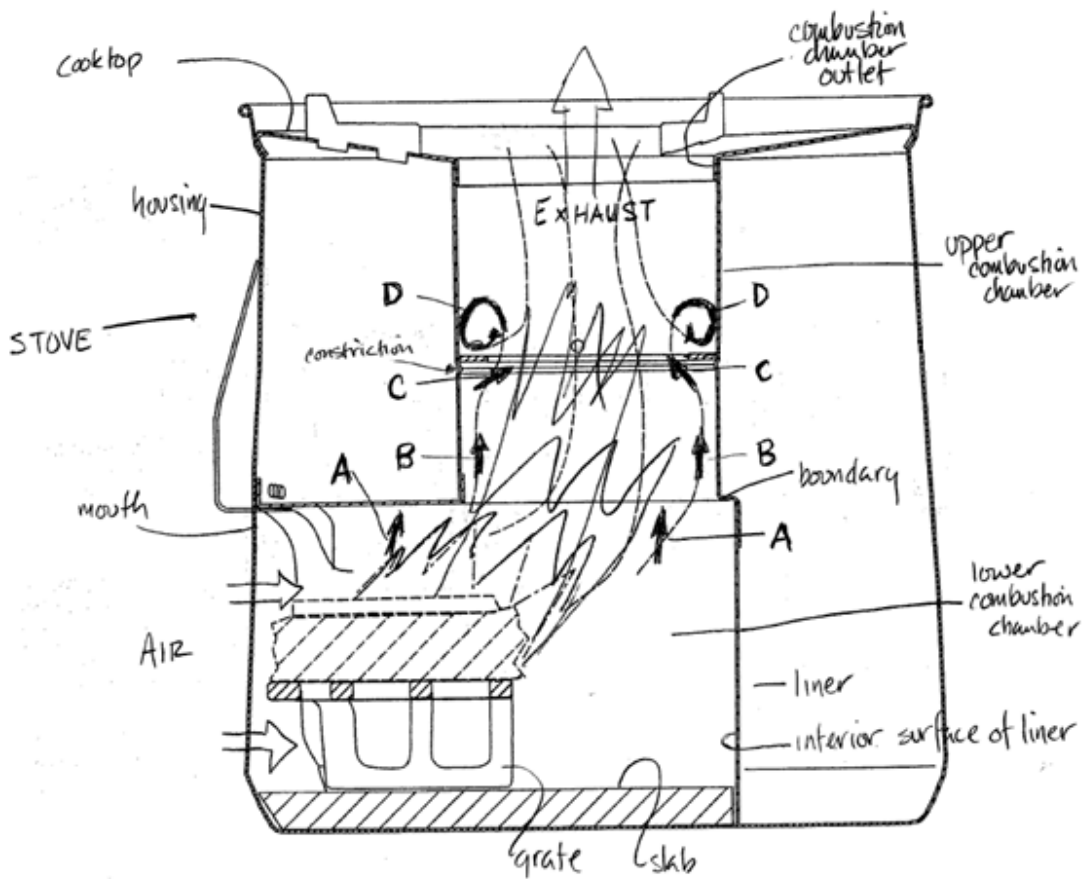
Figure 1-3: Biomass Stove Construction and Flow Path [12]

2.   Indoor Air Pollution

Many factors affect the level IAP an individual is exposed to making the level of risk difficult to predict or quantify. Personal exposure is a function of many factors from emissions concentration, room size and layout, air exchange through the room, and factors unique to an individual such as breathing rate and lung volume.

2.1.   Carbon Monoxide

Inhalation of carbon monoxide (CO) from incomplete combustion has the potential to quickly become life threatening.   As CO is inhaled the ability for blood to transport oxygen is decreased due to the formation of carboxyhemoglobin (COHb). Although they have the potential to bind to the same sites, carbon monoxide has 240 times the affinity for hemoglobin as O_2 does. As a CO molecule binds with an iron site the affinity for oxygen at the three remaining sites increases reducing the rate O_2 can be released. The combination of these factors reduces the amount of oxygen organs can receive [13]. The CO-hemoglobin bond is reversible but the process is slow causing the dangers and side effects of CO poisoning to continue after an individual has been removed from the source [14]. Depending on COHb levels and personal physiology, CO in the blood has a half-life of three to five hours [15]. The colorless, odorless, non-irritating nature of carbon monoxide (CO) makes exposure difficult for an individual to detect [13] [14].

2.1.1. Health Effects

The physical symptoms of CO poisoning depend on exposure time, the concentration of CO inhaled, and personal physiology. The rate of COHb formation in the body is greatest during the first three hours of exposure and then begins to taper off; a steady COHb level will be achieved after six to eight hours of constant exposure in most individuals [16] [17]. Carbon monoxide poisoning affects many regions of the body but damage to organs with the greatest O_2 demands occur first. The muscles of the heart and the brain are at the greatest risk of long term damage from CO poisoning [18]. Physical manifestations of CO poisoning vary between people. Because two people with the same COHb level can exhibit drastically different physical symptoms blood tests are necessary to accurately determine COHb levels. These variations make it difficult to relate COHb levels to physical symptoms [14] but the American Lung Association (ALA) has developed a guide to help medical professionals estimate COHb based on condition at hospital admittance. Table 2.1 has been adapted from ALA guidelines for adult CO exposure [18]. Pregnant women are especially cautioned about CO inhalation due to its effect on the unborn child. Studies have shown that the COHb levels seen in the fetus can be 10-15% higher than that of the mother [16].

% COHb in Blood	Effects Associated with the COHb Level
80	Death
60	Loss of consciousness; death if exposure continues
40	Confusion; collapse with exercise
30	Headache; fatigue; impaired judgment
7-20	Statistically significant decreased maximal oxygen consumption during strenuous exercise in healthy young men
5-17	Statistically significant diminution of visual perception, manual dexterity, ability to learn, or performance in complex sensorimotor tasks

Many factors influence CO uptake in the body but estimations can be made utilizing the Coburn-Forster-Kane (CFK) equation. To predict the percent COHb in the blood the CFK equation makes assumptions and generalization about an individual such as blood volume, diffusivity of CO in the lungs, respiratory rate, and alveolar ventilation rate. While the CFK calculation is just a prediction it can act as a starting point to estimate the level of risk at different CO concentrations. Figure 2-1 was created from the CFK for a range of CO room concentrations [18] [19].
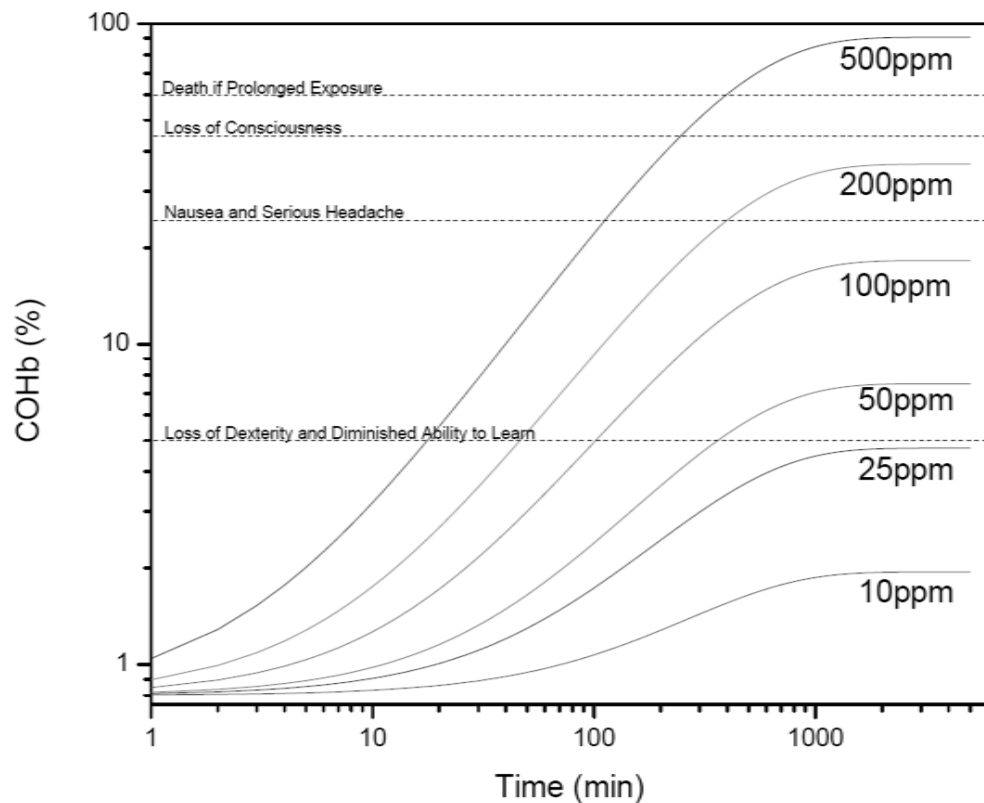
Figure 2-1: Carboxyhemoglobin Estimations for a Range of CO Concentrations

Carbon monoxide poisoning causes both physical and psychological impairments. Chronic exposure to moderate CO levels have been shown to lead to heart enlargement, an increase in blood cell count [17], and neurological impairments such as confusion and memory loss [13] [14]. Many standards have been established in an attempt to avoid serious harm from CO exposure. The exposure guidelines set by the National Research Council (NRC) can be seen in Table 2.2. The immediately dangerous to life or health (IDLH) sets the max concentration of gas at which a person can escape a room in case of sudden exposure. The emergency exposure guidance level (EEGL) is based on the concentration and duration a worker can be exposed to without long term risk. Acceptable exposure levels vary greatly between organizations. The National

Institute for Occupational Safety and Health (NIOSH) has a CO exposure ceiling of 1/7th the 10 minute NRC EEGL level [20]. The World Health Organization (WHO) has established exposure limits, seen in Table 2.3, significantly lower than those suggested by the NRC [16]. The vast difference in exposure limits is based on what each standard considers an acceptable COHb level. The NRC seeks to keep the COHb percentages below 10% compared to the 2.5% COHb WHO deems acceptable [16] [21]. At high enough COHb levels exposure becomes fatal with death usually resulting from cardiac failure [14].

Table 2.2: NRC CO Exposure Guidelines

IDLH	1500ppm
10 Minute EEGL	1500ppm
30 Minute EEGL	800ppm
60 Minute EEGL	400ppm
24 Hour EEGL	50ppm

Table 2.3: WHO CO Exposure Guidelines

15 Minutes	90ppm
30 Minutes	50ppm
1 Hour	25ppm
8 Hours	10ppm

2.2.   Particulate Matter

Particulate matter (PM) can be created during incomplete biomass combustion. These small particles have the potential to have both environmental and health implications. No PM exposure concentration is considered safe but the National Ambient Air Quality Standards (NAAQS) of the Clean Air Act (CAA) has been established as a guideline to minimize the risk. The 1990 standard set a max 24 hour average of

150µg/m^3 for particles smaller than 10µm (PM$_{10}$) in diameter which is not to be exceeded more than once in a year [22]. Particle exposure is damaging for groups of all ages but children have been found to be particularly susceptible to long term health problems; the damage done to children's still developing respiratory systems will last for the remainder of their lives [2]. The increased damage to children's respiratory systems is especially concerning considering that indoor PM concentrations during cooking, a time when children are often times present, can be 10 times higher than other points in the day [23]. An increase of 20µg/m^3 to the average PM concentration of particles smaller than 10µm has been found to raise regional mortality rates by 1% [23].

2.2.1. Elemental vs Organic Carbon

The majority of emissions standards measure particulate matter as a single compound despite the fact that it can be present in two distinctly different forms. Elemental carbon (EC) is what is commonly associated with smoke. This black carbon, or soot, is released during the combustion process and remains chemically stable in the atmosphere. Organic carbon (OC) will be released during combustion but will also be formed through secondary reactions in the atmosphere [24]. The factors controlling combustion OC and the precursors leading to atmospheric OC are not well understood [25]. Making a distinction between the two forms is important when determining the environmental impact of biomass PM. Organic carbon has a global cooling effect where EC has a warming one [26]. Black carbon is thought to be the third largest manmade contributor to the global radiation budget; after carbon dioxide and methane [27]. Comparing the contribution of particles to gases on the global radiation budget is

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difficult due to particles short residence time in the atmosphere [27]. Because the atmospheric lifetime of PM is short the effects of reduced biomass carbon output could be detected in a matter of weeks [28].

The level of impact a compound has on the environment can be represented by its climate forcing magnitude. Climate forcing is the amount of energy per area a compound adds or removes. Elemental carbon is estimated to contribute 0.27-0.54W/m^2 where organic carbon, due to its cooling effect, is (-0.04)-(-0.41)W/m^2. Those values can be compared to carbon dioxide which is approximated to be 1.45W/m^2 [29].

Studies have shown that the fraction of particles contributing to each category can vary drastically. It will be important to determine what controls this distribution if the effect of cook stove generated particles on the global environment is to be understood [26]. Roden *et. al.* have taken extensive measurements of EC and OC from traditional wood stoves. The data was presented as a mass fraction of net carbon (NC), EC + OC. The EC/NC ratio varied from 0.07 to 0.64 and OC/NC from 0.35 to 0.92 [29]. No data was provided on the overall combustion efficiency making it difficult to determine what causes this wide range in composition.

The fuel species and combustion environment can affect the EC/OC ratio. Experiments conducted by the Environmental Protection Agency in wood fireplaces found EC comprises 1-30% on a mass basis of aerosols released during combustion with the remainder mostly OC. Tests repeated in wood stoves produced lower overall PM emissions but had a higher overall EC percentage [30]. As firepower increases particle production can also increase. This increase in particle concentration can be offset by

the increased temperatures which accompany higher firepowers. As temperatures increase more energy is available to consume particles before they leave the flame region. The total mass production and the fraction of EC and OC will be dependent on which of these competing forces dominate.

2.3. Other Compounds of Concern

Carbon monoxide and particulate matter are the most often measured compounds in biomass combustion studies but many other toxic elements will be present. As studies continue on wood cook stoves the production and health effects of other chemicals need to be considered. The level of production of these elements maybe small but there is the potential that they are playing a significant role in lifelong health.

2.3.1. Hydrogen Cyanide

Hydrogen cyanide (HCN) is a colorless gas released during the incomplete biomass combustion. Both the Occupational Safety and Health Administration (OSHA) and NISOH have set ambient HCN exposure limits of 10ppm or less. HCN can be absorbed through the skin or inhaled and causes weakness, confusion, nausea, and anxiety. As concentration increases, HCN exposure will become lethal with death from cellular asphyxiation [31]. HCN and CO have been found to be lethal when mixed even when at their individual sub-lethal concentrations. The combined effects of CO and HCN are not fully understood but studies have shown that the combined reaction rate of each compound with the body is greater than when each is alone [32].

2.3.2. Formaldehyde

Formaldehyde is a suspected carcinogen released during wood combustion. OSHA has set an exposure limit of 0.75ppm but irritation will begin at concentrations as low as 0.1ppm. The eyes, nose, and throat are the first regions affected. Formaldehyde exposure is most commonly from inhalation or ingestion but it can also be absorbed through the skin. H_2CO has been shown to increase the risk of lung cancer at moderate concentrations [33] [34].

2.3.3. Acetaldehyde

Acetaldehyde (C_2H_4O) released during biomass combustion is a known irritant and probable carcinogen. Woodstoves and fireplaces annually produce more acetaldehyde than any other source [35]. Acetaldehyde is found at very low concentrations in ambient air with eye and respiratory irritation in humans beginning at concentrations of 25-50ppm. Acetaldehyde is considered a probable carcinogen but sufficient studies have yet to be conducted to determine its level of risk [36] [35].

2.4.   Room Concentration

The concentration of pollutants which are inhaled is a major factor in determining the risks of exposure. The majority of stove development occurs in laboratory settings where total mass emissions are measured. Although total mass emissions are the simplest way to characterize stove performance this alone cannot predict health risks. Health risks depend on the concentration of pollutants in air. The high cost and time required to perform field measurements of pollutant concentrations

makes developing correlations between concentration and total stove emissions highly desirable.

Models have been developed to correlate production rate and room concentration but they require many assumptions to be made. Most room concentration models for CO and PM assume perfect and instantaneous mixing of pollutants with ambient air. Although this may be valid in some situations, such as a room with large amounts of air movement, the assumption is often times not reasonable. The high concentration of pollutants released and the close proximity of the user to the source makes the assumption questionable when testing cook stoves [37]. The validity of the perfectly mixed room model depends on pollutant species, emissions production rate, room exchange rate, and distance from the source. Empirical data from the field have found large variations in concentration throughout the room in CO and PM while a stove is operating [38].

The time dependent mass of a pollutant in a room can be found in general from equation 1. The common assumption of no pollutant being deposited in the room leads to equation 2.

$$\frac{\partial C}{\partial t} = rate\ in - (rate\ out + rate\ deposited) \tag{1}$$

$$\frac{\partial C}{\partial t} = \dot{m} - \left(\frac{C}{V} * \dot{q}\right) \tag{2}$$

Where:

C – Total mass of emissions in room

m – mass flow rate of emissions into room

V – volume of room

q – volumetric flow rate out of room

Room concentration can be found by dividing the total mass emission by room volume. Equation 2 was used in calculating room concentration for two emissions profiles in Figure 2-2. The profiles are theoretical curves similar to those seen in empirical test data. A room $40m^3$ with 10 exchanges per hour was modeled based on the "average" home size in a developing country [39].
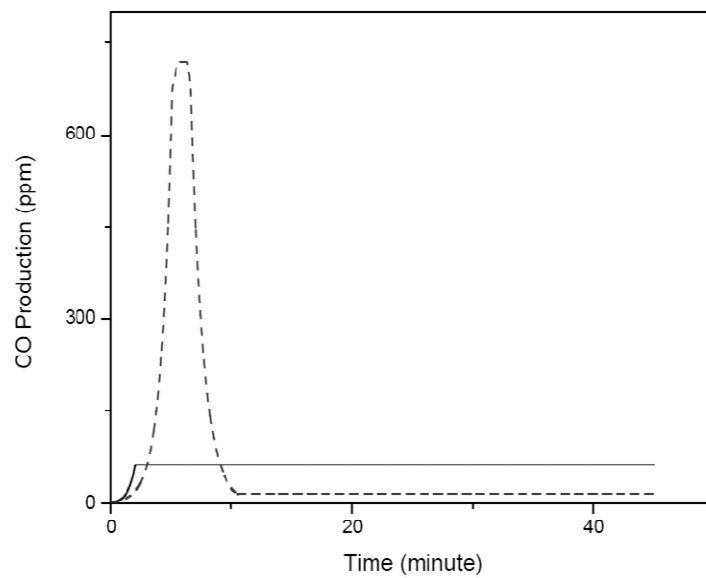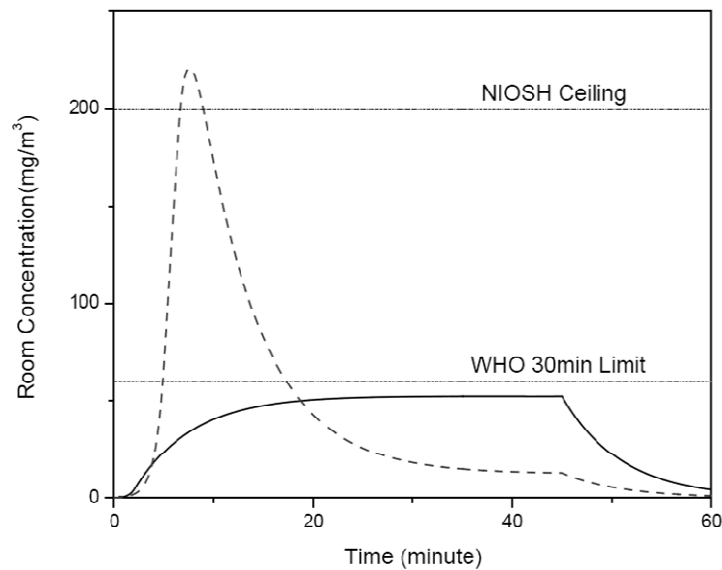
Figure 2-2: Emissions Profiles Achieving the Same Total Production and Different Room Concentrations

Test standards currently in use typically only stipulate a total mass emission limit [40] [41] which is not sufficient to evaluate health risks. Each of the profiles in Figure 2-2 produces the same total amount of carbon monoxide, 15g, but result in very different room concentrations which will have different health implications.

Room concentrations are trivial to calculate using the ideal mixing case but are most likely not accurate for stoves.   A method commonly used to improve accuracy is establishing "microenvironments." A microenvironment is a small zone within the larger heterogeneous room where an assumption of perfect homogenously mixed air is made. The size of microenvironments used differ between models but research done by Ezzati *et al.* has found that this region may need to be as small as 0.125m^3 to be accurate [42] [43]. The location of the stove and user in the room impacts the pollutant distribution and level of exposure which will occur. Changes in location of only one

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meter can double the inhaled concentration [42]. The use of microenvironments

improves the accuracy of room concentration predictions but is dependent on the

assumptions used.

Room concentration calculations become complex as the assumption of ideal

mixing is abandoned. Computational fluid dynamics (CFD) can approximate real mixing

conditions but models typically underestimated concentrations [44]. A CFD prediction of

the constant production CO profile, solid line, in Figure 2-2 can be found in Figure 2-3.

Figure 2-4 is estimated room concentration for two locations in a CFD model and the

ideally mixed room all with the same emissions production profiles. The profiles are

different enough that they would result in significantly different COHb levels. The best

case scenario would not result in any real health risks but being exposed to the worst

would likely result in physical symptoms.
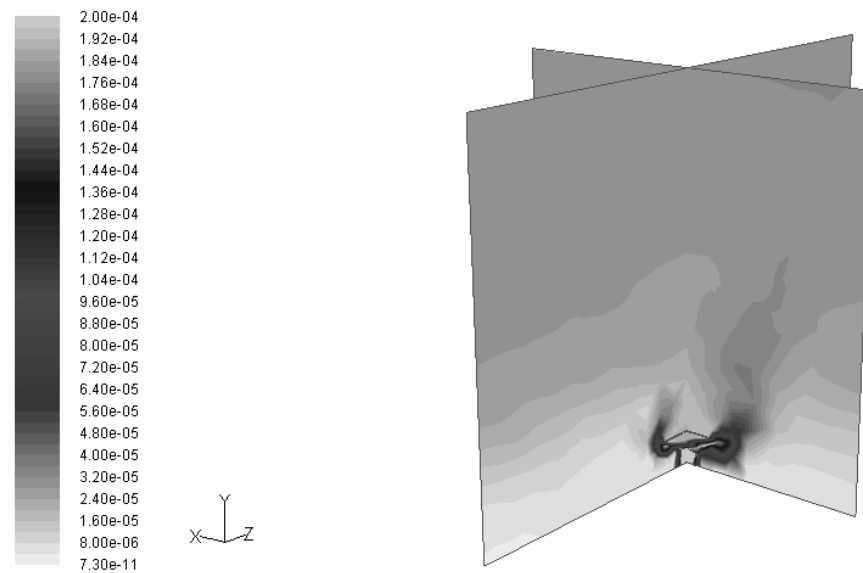
Contours of Mole fraction of co (Time=5.7460e+02)   Mar 19, 2009
                                                          FLUENT 6.3 (3d, pbns, spe, LES, unsteady)

Figure 2-3: Mole Fraction of Carbon Monoxide in Theoretical Room from Simulated Stove
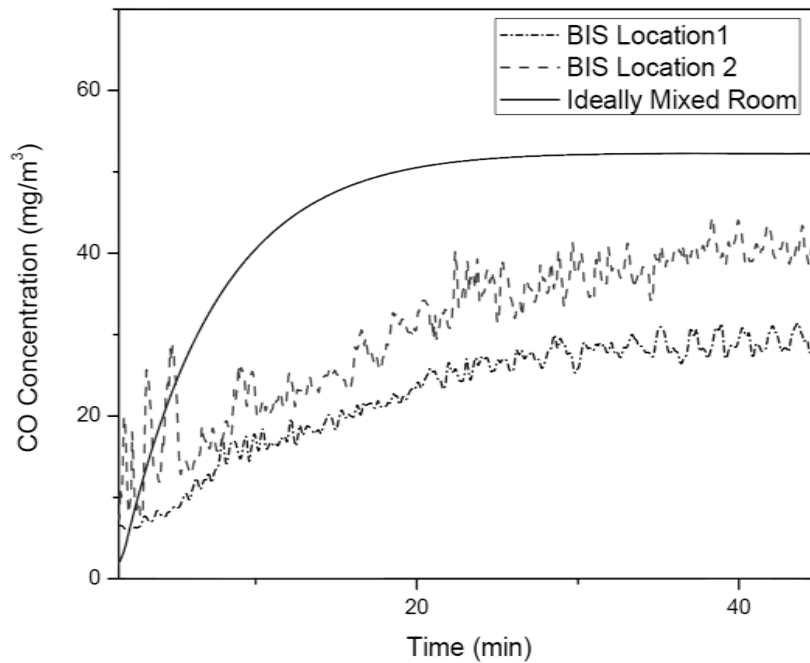
Figure 2-4: Variation in Room Concentration with Location

Although improvements need to be made to current CFD models they appear to provide the most promising means of reconciling laboratory and field data. In order for CFD to become a valid method of predicting ambient room concentrations collaborative work will be required. Systematic, detailed, and replicate data collection of room sizes, air exchanges, and emissions measurements need to be done with CFD validation specifically in mind. The wide range of room conditions will always limit the accuracy of CFD models but they would be an improvement in predicting room concentrations. Once a reliable CFD code as been established it becomes possible to set room dimensions and air exchange rates specific to a region of interest.

3. Test Methods and Experimental Set-Up

3.1. Equipment

3.1.1. Emissions Fume Hood

A constant displacement fume hood was used to capture and evacuate the emissions generated during the testing at a rate of 6 m^3/minute. The exhaust line was equipped with temperature and pressure measurements to calculate real time mass flow through the hood. The hood was 1.2 meters a side at its base and rose 4.3 meters vertically. The top of the hood was fitted with a cap reducing the hood down to a five inch diameter connected to the exhaust pipe. The dimensions of the hood were considered large enough as to not affect the stove while still allowing for a fast response time from measurement equipment. High efficiency particle air (HEPA) filters were installed at the base on each wall to remove background particles from the incoming air. The hood was equipped with ports for thermocouples (TC), relative humidity (RH), and pressure sensors. The fume hood sampling locations and fume hood configuration can be found in Figure 3-1 and Figure 3-2.
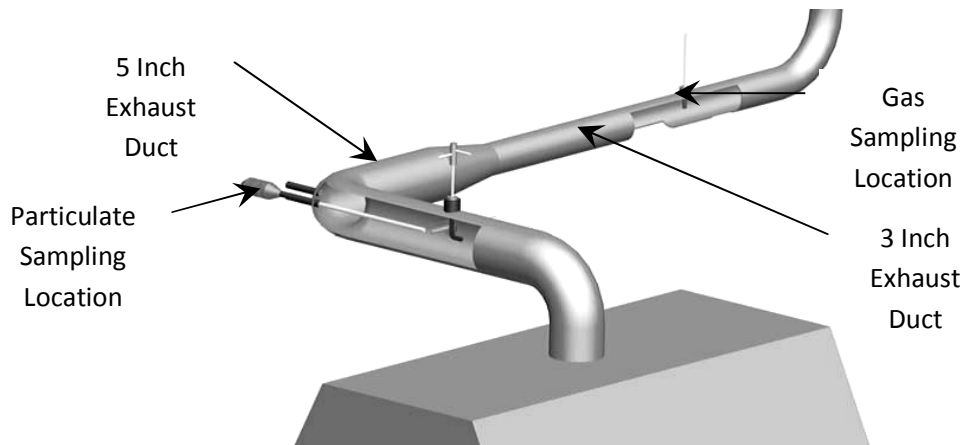
Figure 3-1: Fume Hood Cap and Sampling Locations [45]
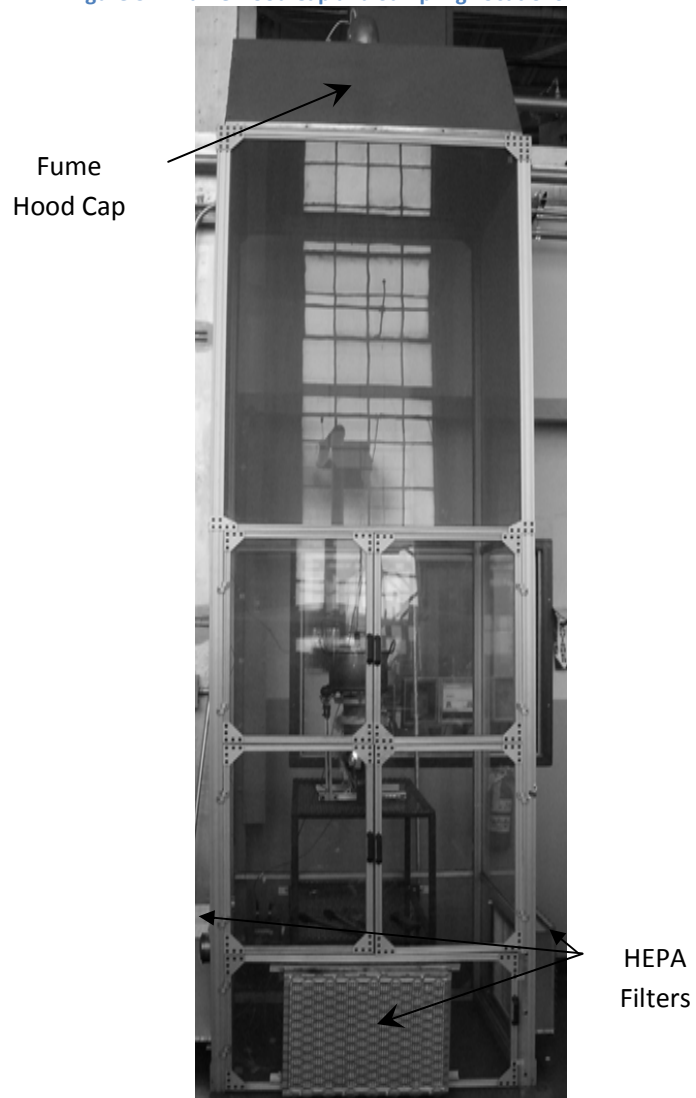
Figure 3-2: Fume Hood

3.1.2. Gas Measurements

3.1.2.1. *Fourier Transform Infrared Spectrometer*

A Fourier Transform Infrared Spectrometer (FT-IR) was used to analyze the gaseous emissions emitted during stove testing. A stainless steel sample probe constructed according to EPA methods was inserted perpendicular to the gas flow path of the exhaust pipe. Samples ran through heated sample lines to the FT-IR where the gases were analyzed. The FT-IR was capable of reporting real time gas concentrations for over a dozen compounds. Before each day of testing the system was zeroed and calibrated following EPA protocols.

3.1.2.2. *Calculations*

The FT-IR reports the molar concentration of each gas measured in parts per million (ppm) at 0.69Hz. FT-IR samples were taken from the exhaust pipe after an approximate dilution ratio of 22. Dilution ratio here is defined as the ratio of volumetric flow through the fume hood to the volumetric flow through the stove. Emissions production from the stoves was calculated by removing background concentrations and accounting for the dilution ratio of the hood. Before the first test of each day a sample was taken from the hood without any stove burning to determine emissions background level. A total mass flow through the exhaust system was calculated from Equation 2 using the temperature and pressure measurements in the exhaust line. Due to the high dilution ratio being used the bulk exhaust flow was assumed to have the same conditions and properties as air. The mass flow of each gas constituent was found from

FT-IR measurements and Equation 4. Total mass production for an entire test for each

gas compound was found using the trapezoid rule.

$$\dot{m}_T = \dot{V} * \rho_T$$
$$\rho = \frac{P*R}{T}$$

[3]

$$\dot{m}_x = \%_x * \dot{m}_T \frac{\rho_x}{\rho_T}$$

[4]

Where:

$\dot{m}_T$: Total mass flow rate through fume hood

$\dot{V}$: Volumetric flow rate through fume hood

ρ_T: Bulk density of fume hood exhaust

P: Pressure

R: Gas Constant

T: Temperature

$\dot{m}_x$: Mass flow rate of constituent "x"

$\%_x$: Percentage of constituent "x"

ρ_x: Density of constituent "x"

3.1.3. Particulate Matter Measurements

Measurements of PM mass were taken following isokinetic sampling techniques.

A stainless steel sample probe was inserted at a 90 degree bend in the exhaust lines to

allow for a straight sampling probe to be used. A 30 degree chamfer was formed on the

leading edge of the sample probe to limit flow disruption. The velocity required to

achieve isokinetic sampling was determined from the volumetric flow rate and exhaust

pipe cross-section and then confirmed with the use of transverse hot-wire anemometer

and pitot tube measurements at the sampling location. To achieve the sampling

velocity of 8.58m/sec a volumetric flow rate of 9.4L/min was required. Total PM_{10} mass

estimations were found from the mass of the sample and the ratio of sample probe to

full exhaust cross-sectional areas. The exhaust pipe area to the sample area was ~680:1.
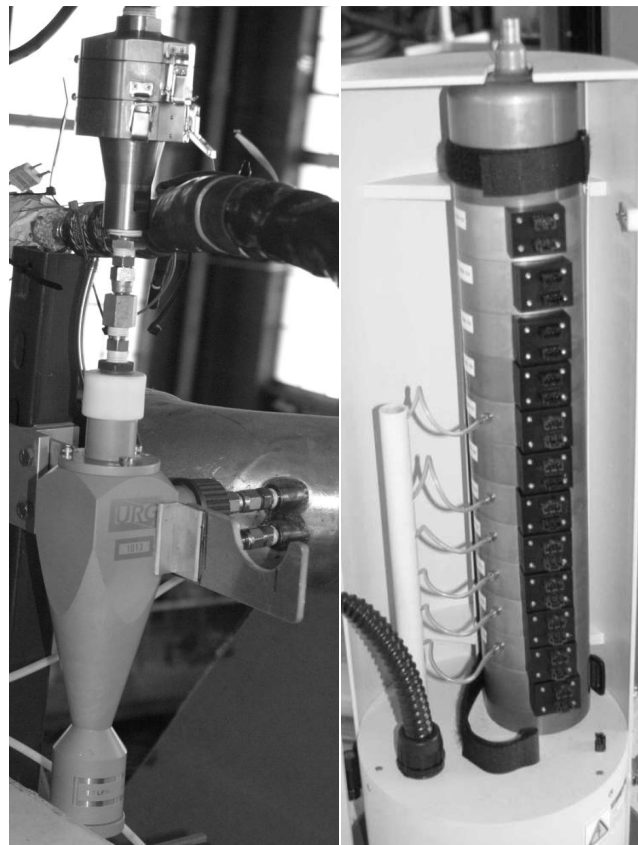
Figure 3-3: Cyclone and Filter Pack and Cascade Impactor Systems

All filter and substrate mass measurements were conducted in a microbalance

lab using a Mettler Toledo MX5 microbalance capable of 1μg accuracy and repeatability.

Balance accuracy was ensured with the use of a 20mg calibration weight before each

measurement session. A laboratory filter or substrate blank was measured each test

day to check for any significant change in mass since previous measurements. The lab

blank was used to check for possible contamination of filter/substrate storage

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containers. The temperature and humidity during measurements were recorded for each measurement session.

The limit of detection (LOD) and limit of quantification (LOQ) for filter and substrate measurements were determined from test blanks. Test blanks were handled following the same procedure as test data up until the point of being exposed to emissions. The blank tests were conducted to determine the effect of the handling and loading processes on test results. The standard deviation between test blanks was used in Equation 5 and Equation 6 to determine the LOD and LOQ respectively. Δm_b is the mass change between pre and post test measurements of a blank. Any mass gain seen on a test filter or substrate below the LOD was considered to have no statistical difference from zero mass gain and measurements between the LOD and LOQ were considered to have gained mass but have no statistical confidence to their numerical value [46]. PM measurements below the LOQ were not included in analysis. The LOD and LOQ for filter measurements and cascade impactor substrate measurements can be found in Table 3.1.

$$LOD = 3 * \sigma(\Delta m_b) \qquad\qquad [5]$$

$$LOQ = 10 * \sigma(\Delta m_b) \qquad\qquad [6]$$

Where:

σ: Standard deviation of measurements

Δm_b: Change in mass of test blank

Table 3.1: Limit of Detection and Limit of Quantification

	LOD (µg)	LOQ (µg)
Gravametric Filter	15	51
Impactor Substrate	17	55

3.1.3.1.   Gravimetric Filter

PM measurements were conducted using Whatman PTFE (Fisher Scientific #05-717-5) air monitoring filters. The filters used had a diameter of 47mm with a 2µm pore size. Filters were placed in a sealed plastic container with filtered air exchange and allowed to come to thermal and humidity equilibrium for at least four hours before weighing.   All weighings were repeated three times. Filters were then loaded into new individual petri dishes until testing. When ready to be tested filters were moved from the petri dish and loaded into Teflon filter holders with stainless steel support ring and then placed in sealed plastic containers. The plastic containers kept the filters clean until the phase in which each filter was to be used was reached. After testing was complete the filter would be removed from its Teflon holder and returned to the original petri dish used. The petri dish was returned to the measurement lab where it was again allowed to equilibrate for at least four hours before being reweighed.

3.1.3.2.   10µm Particulate Cyclone and Filter Pack

Although particles from combustion are typically 1µm or less particles up to 10µm are considered inhalable and pose a risk to human health. To determine the total mass of PM which has health implications all particles below 10µm needed to be considered. A PM cyclone was installed upstream from the filter pack. The PM cyclone uses centripetal force to separate particles. The particle size cut point is dependent on

the volumetric flow rate entering the cyclone and cyclone geometry. A URG-2000-30ENB was used to achieve a cut point as near to 10μm as possible while still conforming to isokinetic sampling. Based on the specifications provided by the URG Corporation a cut point of 13μm was achieved.

The downstream port of the URG cyclone was attached to a URG stainless steel two stage filter pack. The filter pack held the Teflon filter cassettes during testing.

3.1.3.3. Mass Flow Controller

To minimize particulate matter measurement bias, samples were taken under isokinetic conditions. Collected samples will underestimate the true particle concentration if a sample is drawn too quickly and overestimate if drawn too slowly. For the best results the velocity being pulled through the leading edge of the sample probe must be equal to the velocity of the flow going around the probe [47]. Based on velocity measurements at the probe tip a desired velocity of 8.58m/second was deemed necessary for isokinetic sampling. With the diameter of the sample probe being used a volumetric flow rate of 9.4L/minute was required. A vacuum pump and Dwyer Instruments mass flow controller (MFC) (Dwyer Instruments GFC-1133) were used to achieve the desired flow rate. The MFC was calibrated with the use of a DryCal Defender 510 flow meter from Bios International. The MFC was periodically checked for accuracy and readjusted as necessary.

3.1.3.4. MOUDI Cascade Impactor

A NanoMoudi-II cascade impactor from the MSP Corporation was used to determine the mass size distribution of biomass combustion particles. The cascade

impactor uses the principle of particle inertia to separate particles by size. The cascade

impactor was equipped with a built-in MFC set to regulate the flow to 10L/minute. The

flow rate was checked with the DryCal flow meter used with the Dwyer MFC and was

found to be slightly lower than expected at 9.7L/min. A leak check was conducted on

the sampling line from the fume hood to the cascade impactor but the location could

not be found. The slight difference between expected and theoretical flow rates was

deemed acceptable and the tests continued.

The stages of the cascade impactor tower and the substrate plates were

disassembled and cleaned with alcohol before testing. Gaskets were checked for cracks

and replaced when found. A slight layer of grease was applied to the gaskets on the

impactor stages to improve sealing. At the beginning of the tests the top of the cascade

impactor was plugged and the pressure differential between each stage was checked on

the LCD display to check for leaks between stages. Each stage of the impactor, except

for the first and the last, rotate during test to distribute the PM to avoid build-up. With

the cascade impactor wired and running, each stage was cracked apart to check the

stages for rotation. An example of substrates (MSP 0100-96-0573A-X) after testing can

be seen in Figure 3-4.
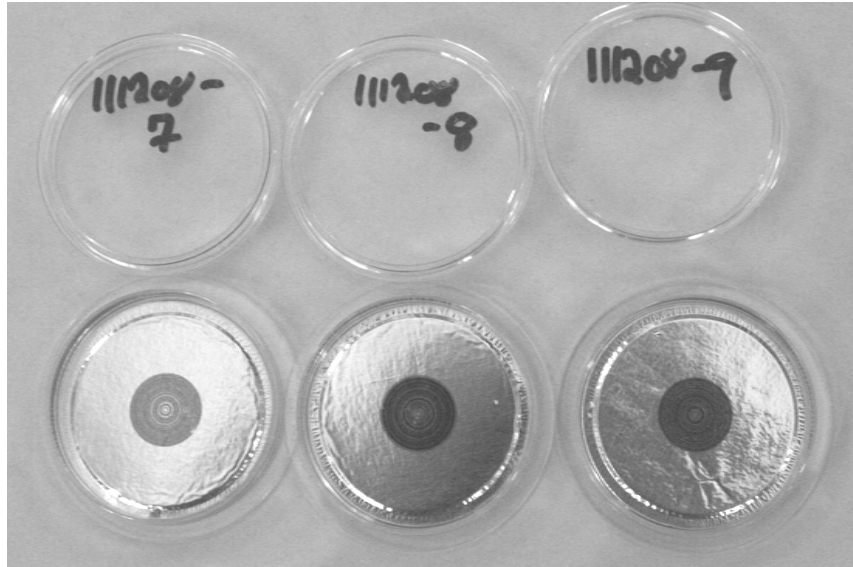
Figure 3-4: Example of Cascade Impactor Substrates after Testing

3.1.4. Secondary Equipment

3.1.4.1. *K-type Thermocouple*

K-type thermocouples (TC) were used for the measuring of water and gas temperatures. The TC temperatures were recorder with a National Instruments data acquisition system and were recorded in real time. The TCs were calibrated with the use of an ice bath to ensure accuracy. When measuring cooking pot temperatures the tip of the TC was placed in the center of the pot and ~2 centimeters from the bottom surface.

3.2.4.2. *Wood Moisture Meter*

A two prong wood moisture meter was used to measure the MC of wood before each test. The meter works on the principle of changing electrical resistively depending on MC. The readings from the moisture meter were compared against the "oven dry method" of MC measurements to ensure accuracy. The oven dry method works by

weighing sample pieces of fuel and then heating the fuel to just above the water boiling point to evaporate all moisture. After allowing to completely dry the samples were reweighed to determine the mass of water of wood present in the samples.

4.   Testing Standards[1]

4.1.   Background

Many groups have worked to develop and disseminate clean burning high efficiency stoves with varying degrees of success. Despite the nearly 30 years of modern biomass stove development a universal testing standard has yet to emerge. The standards and testing methodologies that are currently used fail to address many of the factors effecting performance or rely on unreasonable correction factors. The aim of this study is to determine the effect of controllable parameters on the performance of a biomass stove.

4.1.1.   Volunteers in Technical Assistance

The first serious effort at a testing standard for biomass cook stoves was developed by Volunteers in Technical Assistance (VITA). In 1982 VITA published a stove performance test to facilitate in comparing cook stove designs. As stated in the opening paragraph of the Water Boil Test (WBT) standard, the test was "intended to help stove designers understand how well energy is transferred from the fuel to the cooking pot". The WBT was revised first in 1985 and again in 2007. The test revisions included the removal of lid use, increased simmer time from 30 minutes to 45 minutes, and the addition of a second boiling phase. The most significant change from the original VITA

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[1] Chapter is reproduction of DeFoort, M & L'Orange, C. *Influence of Testing Parameters of Biomass Stove Performance: Evaluation of Testing Methodologies*. Submitted to Biomass & Bioenergy.

test standard was in the calculation of thermal efficiency. The 2007 revision of the WBT considers the energy put into vaporizing water as useful energy instead of wasted [48].

The WBT is a three phase test in which a pot of water is twice brought to boil and then held at a simmer. In the first phase, the "cold start", 5 kg of water are brought to a boil with the stove at ambient room temperature. The test is then repeated the stove body already hot, termed the "hot start". Immediately following the hot start the water is held at a simmer for 45 minutes [48].

4.1.2. Bureau of Indian Standards

In 1983 the Indian government, through the Department on Non-Conventional Energy Sources (DNES), began a program to promote the use of improved biomass stoves. Started by the DNES, the National Programme on Improved Chulhas (NPIC) was trying to reduce fuel use, limit deforestation, and improve air quality in the home [49]. As part of the program the Bureau of Indian Standards (BIS) has developed a certification process for the testing of biomass stoves. The certification process is optional for manufactures but is designed to ensure safe, high quality products for the consumer. The BIS standard protocol uses a set amount of fuel, based on heat production rate of the stove, and determines the amount of thermal energy which can be transferred to a pot. The stove is lit and pots of water are repeatedly heated to just below the boiling point until all the fuel has been consumed [41].

4.1.3. The State Standard of the People's Republic of China

The largest improved stoves program to date was conducted by the Chinese Stove Program. *The Testing Method for the Heat Properties of Civil Firewood Stoves*

takes a standard amount of fuel and heats a pot of water to boiling and then keeps that

pot at simmer until the temperature cannot be sustained. A specific pot size is not

specified but pot the pot is filled 2/3 full. The mass of fuel to begin the test with is set to

be 1/7th to 1/5th of the initial water mass [50].

4.2.   Background on Combustion and Heat Transfer in Biomass Stoves

4.2.1. Combustion Process

Biomass combustion is an inherently complex process involving liquid, solid, and

gas phase reactions occurring simultaneously. Over 200 gas compounds have been

identified during the combustion process. Variables from fuel composition to wood

knots and growth rings have been shown to affect the combustion process [51]. The

burning of wood can broadly be broken into 4 general stages: fuel drying, pyrolysis,

combustion, and surface oxidation [52]. The stages of wood combustion will transition

from one to the next as temperatures increase as seen in Figure 4-1 [53].
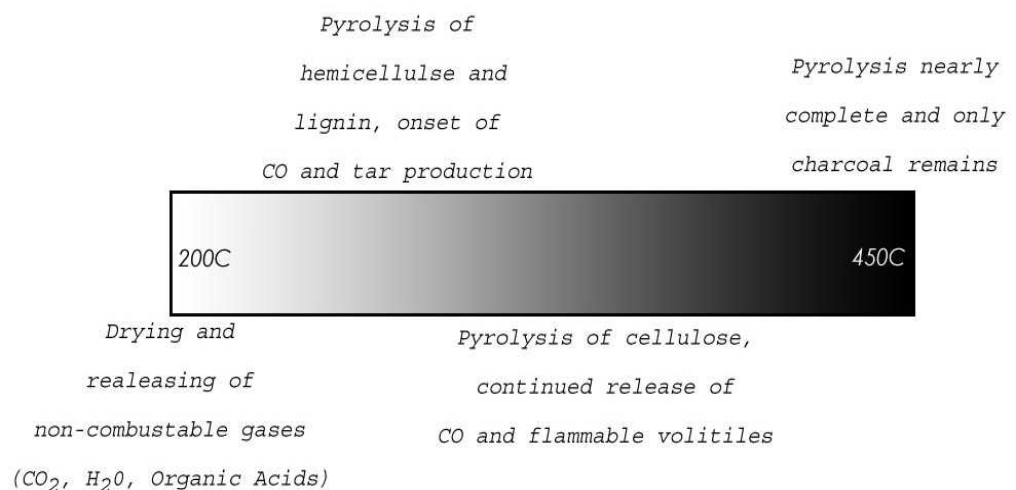
Figure 4-1: Stages of Wood Combustion with Respect To Temperature

4.2.2. Drying

The water trapped in a piece of wood limits the temperature it can reach. Until all the water has vaporized from a section of wood its temperature is limited to the boiling point of water. The greater the amount of moisture in the wood the longer it will take for a section of wood to be able to move to the next stage of combustion; pyrolysis [54].

4.2.3. Pyrolysis

Pyrolysis is the process of heating a material to the point it begins to chemically degrade. As wood is heated the bonds inside begin to vibrate. As the temperature rises the intensity of the vibrations increase become until the bonds fail releasing volatile gases [55]. During pyrolysis hydrocarbons such as methane and acetaldehyde will be produced along with CO_2, CO, hydrogen gas, and water vapor. Most pyrolysis processes will also produce tars in the form of creosote and pitch [56]. These tars are corrosive and have the potential of clogging the stove or igniting causing chimney fires [57]. The products which are released during combustion are a function of the heating process and the chemical composition of the original fuel [56].

The structure and composition of a fuel influences how the pyrolysis process will progress. Wood is composed of long bundles of tubular fibers forming the grain of the wood. Variations in the arrangement and composition of these fibers are responsible for the different properties wood species exhibit. Wood is composed of three primary components: cellulose, hemicellulose, and lignin. Cellulose accounts for roughly 50% of wood on a mass basis, and makes up the majority of the cell walls in the fiber bundles.

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Hemicelluloses is similar in chemical composition to cellulose except where cellulose has a well ordered structure hemicellulose is comprised of amorphous random bonds. Hemicellulose helps to bind the cellulose bundles together. Lignin is what makes it possible for individual wood cells to hold together. The percentage of lignin in wood varies between species but is typically 15-30% for most wood species [58]. The remainder of the wood is composed of inorganic materials, usually referred to as ash. The composition and quantity of ash present will change with location in the wood and between wood species [56].

Wood is typically considered to have two regions, the sapwood and the heartwood. Both are comprised of cellulose, hemicellulose, and lignin but behave very differently. Sapwood lies directly below the bark layer of tree and is mix of both living a dead wood cells. It is the main food storage system for the tree. Moving deeper into the tree more of the cells are dead and is termed the heartwood of the tree. The heartwood has very little moisture movement or nutrient storage but provides stability and structure to the tree [58].

4.2.4. Combustion

As the gases formed during pyrolysis move away from the surface of the wood they will mix with the ambient air. If the gases have the opportunity to mix sufficiently before leaving the reaction zone they may undergo combustion [55]. If the gases do not have the energy and oxygen needed they will "escape" the flame region producing PIC or condensing into smoke [59]. The limiting factor in the combustion process is usually the rate at which volatile gases can mix with oxygen [54]. Typically two-thirds of the

energy released during the burning of wood comes from the combustion of the gases [51].

4.2.5. Surface Oxidation

The charcoal which remains after pyrolysis still contains significant energy which it can contribute to the system. The carbon surface of the charcoal will react with oxygen in the air and form into either carbon monoxide or carbon dioxide both releasing energy to the surroundings [60]. The rate at which the charcoal oxidizes is a function of the rate oxygenated molecules can reach the fuel surface [60] [61]. As solid carbon is pulled from the charcoal an ash layer, composed primarily of silicon dioxide and calcium oxide [56], is left behind. The ash layer acts like insulation reducing heat transfer from the charcoal surface and slowing the overall oxidation process. As the surface temperature of the charcoal rises above 1300K the reactions forming CO dominate over the formation of CO2 [61] and large amounts of toxic gases are released.

4.2.6. Influence of Radiation

Energy in the form of radiation makes up a small percentage of the total energy released during combustion but has a significant impact on sustaining the combustion process. As radiation is emitted a portion of the energy is reabsorbed by the fuel providing the energy needed for continued decomposition and combustion [54].

4.3.   Heat Transfer

Traditional stoves typically have thermal transfer efficiencies of less than 15% [11] [62]. These low thermal efficiencies are due to a large fraction of the energy being produced being considered wasted which may not always be accurate. Energy from the

combustion process can be split into four groups: energy into the pot, energy to sustain pyrolysis and combustion, energy to heat the stove, and energy which escapes from the stove. There is usually no disagreement that energy into the pot and sustaining combustion is "useful" but the other two categories are questionable. Depending on the situation the heating of the stove body and the releasing of hot gases into the room maybe desirable, such as locations where the stove is also used as a room heater. When determining the thermal efficiency of the stove it needs to be decided what energy is useful and what is wasted.

The fraction of the energy which falls into each category depends on the stove being used and how it is being operated. The energy needed to sustain combustion is a function of the combustion rate and ambient conditions and typically quite small [54]. The heat transfer to the pot is a function of its relation to the fire and the hot gas path around the pot. The energy absorbed by the stove body increases as the specific heat, the surface area, and the mass of the stove increase. The fraction into each category will change with time. As the stove and pot temperatures change the energy transfer will change. Thermal efficiencies are typically calculated for an entire test but the real-time thermal efficiency of the stove varies throughout the test.

4.4.   Analysis of Testing Procedure

The goal of any testing standard is to define a procedure that is highly repeatable and representative of real conditions. When developing a standard it is crucial to minimize the influence of conditions that can change the results of the test. Testing standards have traditionally fallen into two categories: tests based on energy transfer

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and those based on completing a task. Task oriented protocols have the advantage of capturing the nature of the stove and predicting the stove performance the end user will experience. The drawback to task based testing is increased variability. An energy transfer test inherently allows for more control and repeatability however may fail to capture the nature of how the stove will perform in the field. By following an energy transfer method the ambiguity of test duration is greatly diminished.

4.4.1. Successes, Limitations, & Goals of Test Protocols

The testing standards currently in use are split between task and energy transfer based. Both the Indian and Chinese testing standards determine the extent of energy which can be transfer to the pot regardless of method or rate. Neither standard considers how the stove is going to be used by the cook but both standards have achieved an accurate method of determining heat transfer efficiency. The length of the tests also provided adequate time smooth out the transient behavior of the stove. The VITA WBT test requires stoves to complete the same tasks the cook will ask of them but has the possibility of too much variation to achieve good comparisons.

After reviewing the testing standards of biomass stoves already in use it was decided to create a hybrid of several different protocols. The goal was to achieve a test which captured the best of each test while addressing some concerns surrounding existing methods. The proposed protocol relies on a task based test while better controlling energy transfer.

4.4.2. Energy Transfer

A test protocol based on energy transfer appears to be the best solution but the impacts of variable boiling temperatures are still a problem. As the boiling point is approached and vaporization begins the net energy into the water becomes difficult to measure. The temperature at which boiling occurs is dependent on altitude, ambient barometric pressure, and water purity and changes with location and can change throughout the day. As can be seen in Figure 4-2 the ambiguity of when boiling is reached can cause considerable variability in a test. With the use of a single fixed temperature, below the boiling point, all stoves are required to transfer the same amount of energy regardless of location or ambient conditions. Correction factors have been used in the past to account for testing in different locations [48], but a better solution is to change the temperature range the water is being heated.
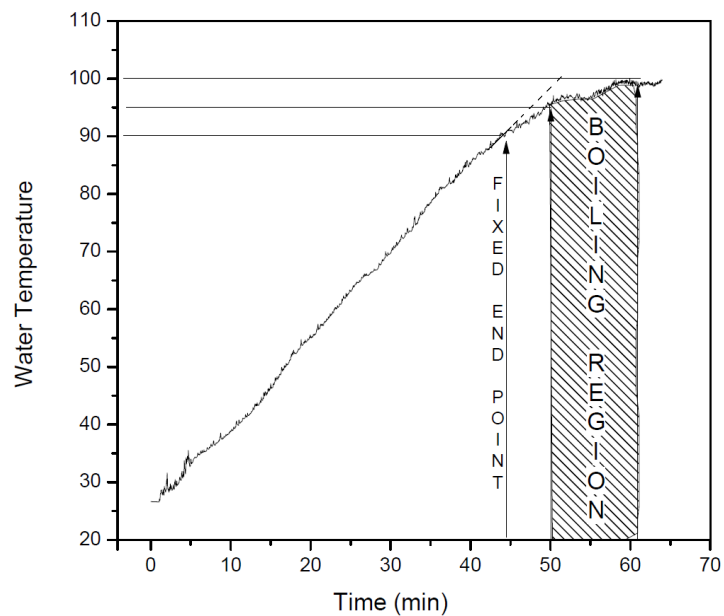
Figure 4-2: Effect of Vaporization on Boiling Point and Temperature Profile

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As water approaches its boiling point vaporization occurs. The net energy added

to the water is a function of both heat transfer to the water and heat transfer from the

water in the form of steam. Returning to Figure 4-2, the dashed line represents the

progression of water temperature if no vaporization occurred. Real water temperature

profiles will deviate from the ideal as energy is lost from the water due to vaporization.

Correcting for vaporization is a challenge because the amount of energy lost is

dependent on the temperature at which the phase change occurs. Figure 4-3 shows

how slight differences in boiling temperature have a large impact on completing a test.

Take the example in Figure 4-3 where one test has a boiling temperature of 99°C and

the second test of the day should have boiled at 100°C. If both tests were stopped

when the boiling temperature of the day (99°C) was reached the variation in test time,

Δt_2, is more than 5 times that if both tests were stopped at 90°C, Δt_1. In an ideal case no

energy leaves the water in the form of steam and the heat transfer to the pot can be

calculated using equation 7. With vaporization the real heat flux leaving the pot as

steam can be found from equation 8. In most testing situations the mass rate of water

vaporization is not known to any degree of accuracy making the equation impossible to

solve.
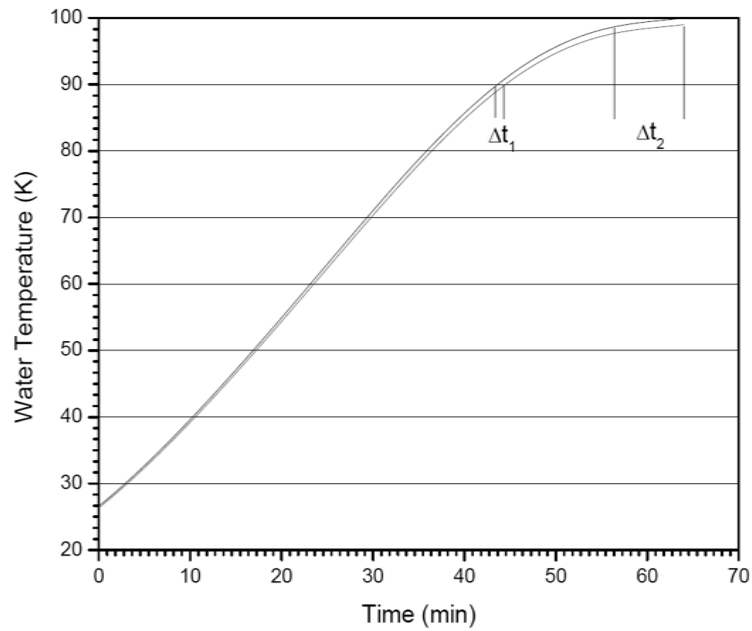
Figure 4-3: Uncertainty Caused from Uncertain Boiling Temperature

$$q_w = m * C_p \frac{dT}{dt} \qquad [7]$$

$$q_v = h_{fg} * \frac{dm_v}{dt} \qquad [8]$$

Where:

q_w: heat flux into water (W)

q_v: heat flux leaving the water in the form of steam (W)

m: mass of water in pot (kg)

C_p: Specific heat of water (kJ/kg-K)

dT/dt: temperature rate (K/sec)

h_{fg}: heat of vaporization (kJ/kg)

dm_v/dt: mass rate of water vaporizing (kg/sec)

To determine if the repeatability of tests could be improved by reducing phase

change an experiment was conducted where vaporization energy was recaptured.   A

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pot filled with 15°C±1 water was placed on an electric burner and allowed to heat to 90°C. The same pot was then refilled and reheated with a piece of 2inch rigid foam insulation on the surface. The time to heat and the mass of water vaporized was measured for each arrangement and each arrangement was conducted 3 times.

The use of insulation reduced the amount of vaporization which occurred as would be expected but it also reduced the amount of variation between tests. When insulation was not used the standard deviation between tests was nearly 2% of the total energy. When insulation is used the standard deviation dropped nearly 4 fold to just over 0.5%.

Several possible solutions to the vaporization problem were considered before deciding on the use of insulating foam. The original VITA test procedure called for the use of a pot lid during test but was removed for simplicity [48]. While a portion of the vaporized water will contact that lid surface and condense back into the water a large fraction will remain in the gas phase trapped between the water surface and the pot lid. The tightness of the lid and the distance between the water surface and the lid will change how much vaporization occurs during the test. Another option which was considered was the heating of a fluid where vaporization is less likely such as glycol or oil. The concern with both alternative fluids was the increased risk of burns and the fluid's low specific heats. The specific heat of most oils and glycol is less than half than that of water. With the much lower specific heats of oil and glycol very little energy needs to be transfer to the liquids before temperatures get above the range where they are safe to use.

4.5. Experimental Procedure

After considering the concepts presented in section 4.4 a modified WBT procedure was developed which addresses many of the concerns from previous test methods. To reduce the impact of vaporization and the need for testing location correction factors the temperature testing range was lowered to 15°C-90°C. A layer of foam insulation was placed on the surface of the water during the cold and hot start phases of the test to further reduce the variability of vaporization. The revised WBT keeps the practice of holding water at a constant temperature for 45minutes without being covered. The uncertainty associated with water vaporizing during the simmer phase is still a concern but it is necessary to determine the low power capabilities of a stove. It is felt that with lowering the simmering temperature (90°C) and keeping a set test length, the uncertainty inherent with the test becomes acceptable. As metrics of stove performance three factors were investigated; carbon monoxide (CO), particulate matter (PM), and wood use. The carbon monoxide and PM data reported represent the total mass emitted during the cold start phase of the modified WBT. When wood use is reported the mass represents the mass of the wood if no moisture was present. The stove was burned in a fume hood sufficiently large to capture all the emissions of the stove with filtered inlet air to remove background PM. CO was measured using a Fourier Transform Infrared Spectrometer (FT-IR) and PM was isokinetically sampled onto Teflon filters and measured using gravimetric analysis. A balance capable of measuring to 1 microgram accuracy and repeatability was used. Multiple iterations of

each test were conducted with the average of the tests reported here. The uncertainty

of each test group is reported in the form of standard deviation.

4.5.1. Parametric Testing

Using the new protocol tests were conducted to determine which test

parameters lead to variability. The goal was to determine what variables need to be

controlled in the standard to allow comparison of results. Baseline conditions were set

and each test changed a single parameter at a time. All combustion tests were

conducted on an Envirofit International model B1100 stove as seen in Figure 4-4.

Douglas fir at 7% (dry basis) moisture content at 1.5cmx1.5cmx30cm was used as a

baseline fuel condition. The baseline was set based on the moisture content achieved at

ambient conditions and the most convenient size to cut the wood. The parameters

tested and the number of replicates performed can be found in Table 4.1.
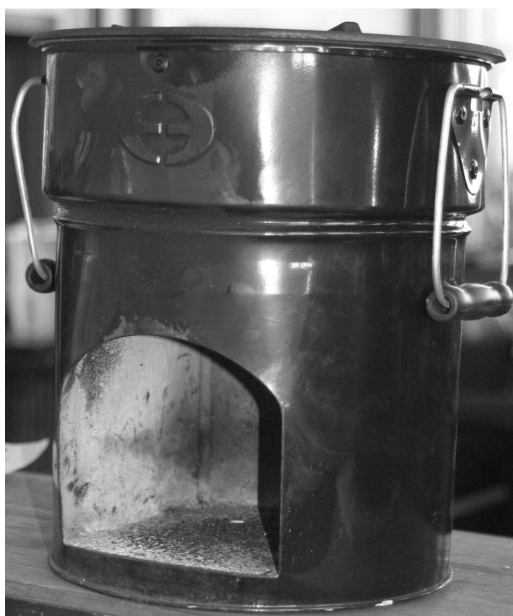
Figure 4-4: Baseline Stove, Envirofit International

Table 4.1: Parametric Testing Matrix

Test Parameter	Test Version	Replicates
Fuel Geometry	Small	3
	Medium	3
	Large	3
Fuel Moisture Content	4%	2
	7%	3
	13%	2
	30%	2
Pot Geometry	#1	3
	#2	3
	#3	3
	#4	3
	#5	3
	#6	3
Pot Insulation	No Insulation	3
	Insulation	3
Total		42

4.5.2. Fuel Geometry

The anisotropic nature of wood controls many of its properties including thermal conductivity. Thermal conductivity plays a large role in the heat transfer of the fuel affecting its pyrolysis. Conductivity along the grain can be twice that running perpendicular to it. For maximum heat transfer a piece of wood should have a large cross-sectional area while maximizing the total surface area. For a given mass multiple small pieces will have greater total surface area while minimizing the depth heat needs to penetrate. For geometries of equal proportions the surface area to volume ratio increases and volume decreases. With increasing surface area the absorbed radiation from the fire grows, increasing fuel consumption rate [54].

The effect of fuel configuration was tested by conducting the modified WBT with 3 different wood geometries. Small (0.75cmx0.75cm), medium (1.5cmx1.5cm), and large (3cmx3cm) samples were tested, each with a length of 30cm and square cross-section. 3 tests were conducted at each wood size.

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The wood geometry tests show that the effect of fuel size on carbon monoxide

emissions and wood use is insignificant. It was found that PM decreases with increasing

wood size, but there is significant uncertainty in the results. The decreasing PM with

increasing wood size maybe due to the reduced number of times new wood is added to

the stove. Particulate matter can form both from incomplete combustion and from

abrasive wear and each time new wood is feed into the stove the partially burned wood

and char is disturbed creating the potential of entraining PM into the exhaust stream [47].

From the current results wood geometry cannot be said to impact particle production

but further replicates should be repeated to explore PM production. The effect of fuel

size on emissions and fuel consumption can be seen in Figure 4-5. The error bars in

Figure 4-5 and all subsequent graphs is the standard deviation between test replicates.
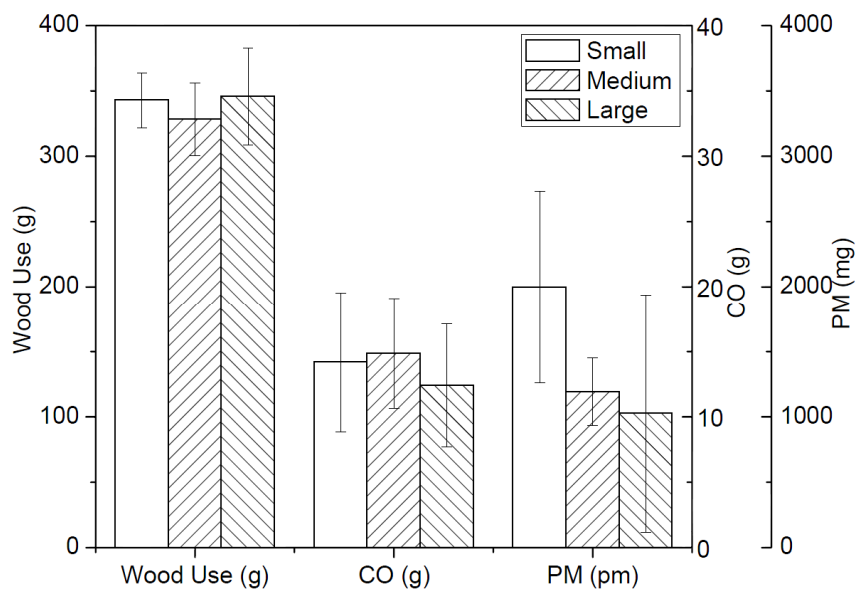
Figure 4-5: Effect of Fuel Size on Wood Use, Carbon Monoxide, and Particulate Matter

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4.5.3. Moisture Content

Wood will reach moisture equilibrium if allowed to cure with the resulting moisture content strongly dependent on the ambient temperature and relative humidity. Equilibrium moisture content of wood can vary from 1% to 25% in normal temperature and humidity conditions [63]. The net calorific value available in wood depends on moisture content. The moisture in the wood requires energy to be heated and vaporized allowing the fuel to reach pyrolysis and combustion temperatures. As the moisture content increases the net calorific value decreases as seen in Figure 4-6 [64]. Previous studies have shown that while moisture in the wood decreases the total energy available for cooking some moisture in the wood may slow the pyrolysis reactions increasing the resonance time in the combustion zone improving total emissions [54].
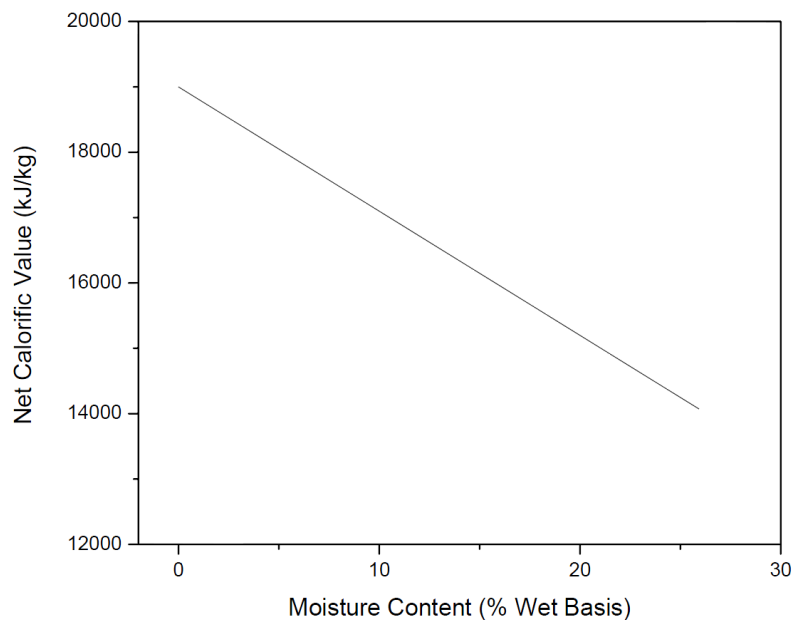
Figure 4-6: Effect of Moisture Content on Net Calorific Value

To determine the effect of moisture content on combustion samples of wood at four different moisture contents were tested. The moisture content of the wood was measured with a Delmhorst J-4 handheld moisture meter. Accuracy of the moisture meter was confirmed with the oven-dry moisture measurement method.[2] A sample was dried to 4% by being placed it in an electric kiln set at 90°C. The moisture of two samples was increased to 13% and 30% respectively by being placed in a humidity controlled chamber and allowed to reach equilibrium. Before testing all samples were placed in individual buckets with air-tight seals and allowed to stabilize to ensure uniform moisture distribution.

A slight increase in fuel use was seen as moisture content increases from 7% to 30% but the differences are not significant. All tests, with the exception of 7% MC, had their averages fall within the standard deviation bars of the remaining tests. More fuel was also required for dry wood which may be an indication an increased fuel consumption rate. As shown in Figure 4-7 as moisture content increases the total wood required to complete a task increases slightly. This implies that while the net calorific value changes with moisture content the rate of energy being transferred to the pot does not. Moisture content also has a significant impact on the emissions released during the combustion process. The addition of moisture improves both CO and PM emission until the wood becomes too moist and combustion is inhibited causing a rise in gaseous and PM emissions.

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[2] For the oven-dry method a sample of wood is weighed and then heated until no moisture remains. The dry wood is then reweighed.

$$\%MC = \frac{Mass_{original} - Mass_{dry}}{Mass_{dry}} * 100$$
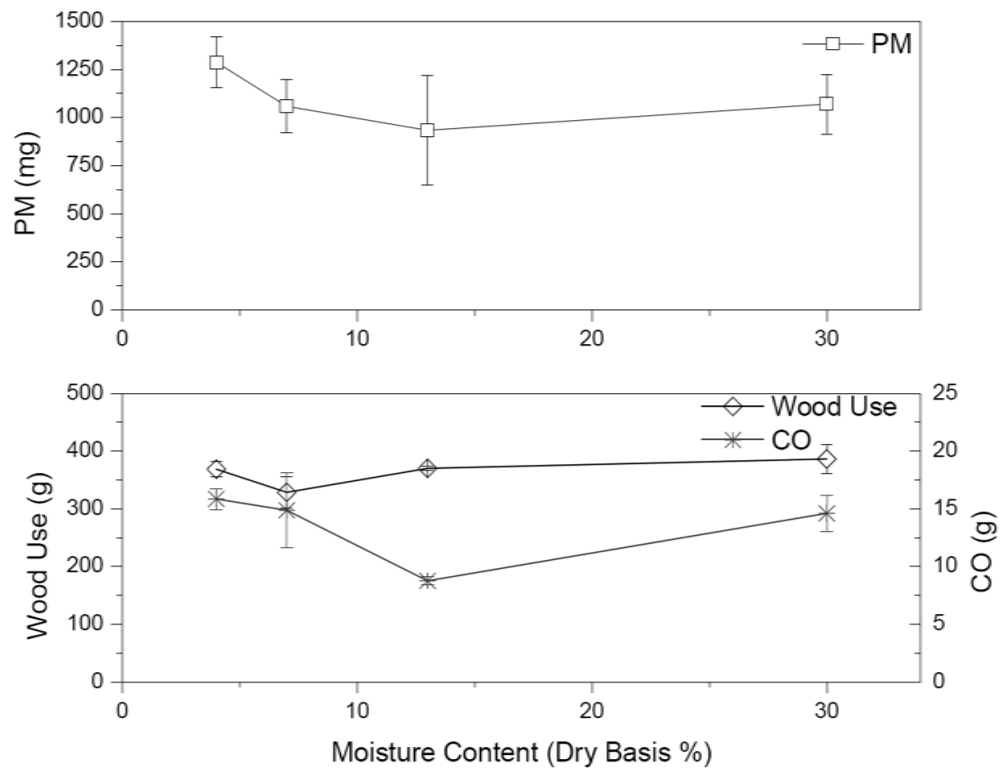
Figure 4-7: Effect of Moisture Content on Wood Use, Carbon Monoxide, and Particulate Mater

4.5.4. Pot Geometry

The pot used has the potential to affect the performance of a stove. As the surface area of the pot increases the net heat transfer increases, reducing time to boil and fuel consumption. As seen in Figure 4-8 as the pot diameter grows the total surface area of a 5L pot decreases until the pot diameter approaches 10cm. Beyond this critical diameter the net change in surface area with changing diameter is very small. Above that diameter heat transfer to the pot should be similar regardless of pot geometry. If no insulation was placed on the water surface the geometry of the pot would have a larger influence due to the increased water surface area exposed to vaporization. The pot wall thickness and material also have the potential to affect stove

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performance. An overall heat transfer equation was used to calculate the impact of

changing pot thickness and material on total heat flux found in Equation 9. A basic heat

flux model of convection to and from a solid with constant gas and fluid temperatures

was used. Figure 4-9 presents normalized heat flux plots with changing pot material

conductivity. While wall thickness and pot material can vary considerably between pots

the change in heat flux will be insignificant. When Equation 9 is examined it can be

found that the convective heat transfer coefficient of the gas will dominate the total

heat flux through the cooking pot. Regardless of how the pot construction changes the

transfer conditions of the gas will dictate heat flux through the pot.
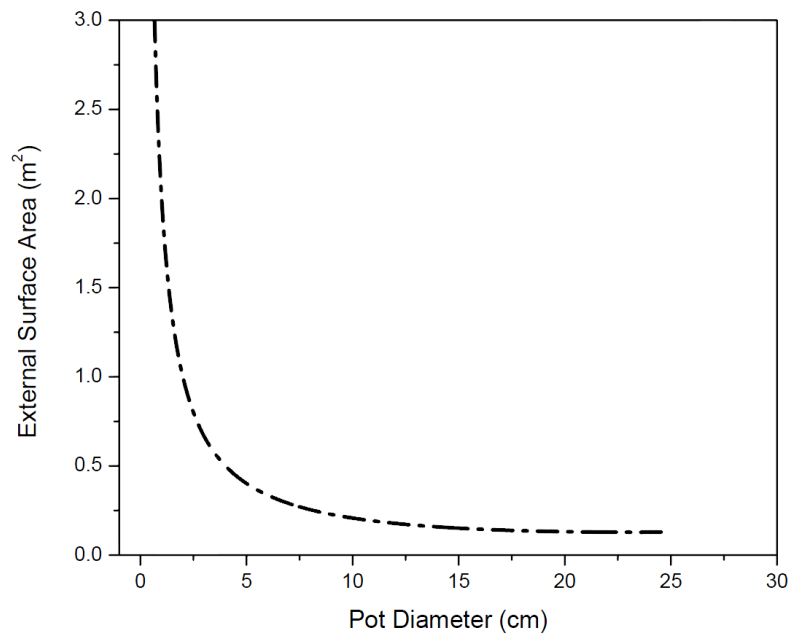
Figure 4-8: Surface Area vs Diameter of a Constant Volume Cook Pot
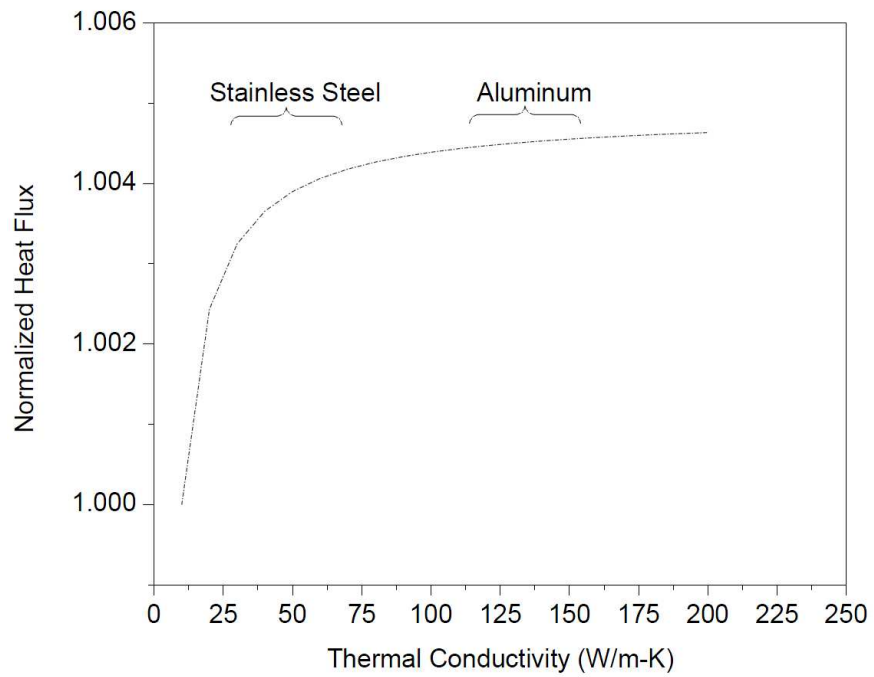
Figure 4-9: Influence of Pot Conductivity on Heat Flux into Pot

$$q = \frac{T_w - T_g}{\frac{1}{h_g} + \frac{\Delta x}{k} + \frac{1}{h_w}}$$ [9]

Where:

q: heat flux (W/m^2)

T_g: temperature of gas below pot (T)

T_w: temperature of water in pot (T)

h_g: convective heat transfer coefficient of gas, used 50W/m^2-K

h_w: convective heat transfer coefficient of water, used 2000W/m^2-K

Δx: thickness of pot wall (m)

k: thermal conductivity of pot material (W/m-K)

6 pots were tested with 3 tests per arrangement to confirm the theoretical calculations. Pot specifics can be found in Table 4.2. Pots were filled with 5kg±0.005 of 15°C±2 water and heated on a propane burner for 10 minutes. A propane burner was used to reduce the impact of the user on the results. The mass of propane burned was recorded for each test to ensure each pot was supplied with an equal amount of energy.

Table 4.2: Materials and Dimensions of Pots Used During Parametric Testing

Pot	Material	Width (cm)	Height(cm)	Mass(kg)
1	Stainless Steel	25.5	25.5	0.75
2	Stainless Steel	25.5	16.5	0.83
3	Stainless Steel	23	20	0.65
4	Aluminum	25.5	18	0.32
5	Porcelain Coated Mild Steel	24	18.5	0.58
6	Porcelain Coated Mild Steel	35.5	25.5	1.19

The changes in temperature seen by the six pots were all within 2.5°C of each other. While pot geometry and material has a slight impact on heat transfer 4 of the 6 pots performed nearly identically with pot 1 experiencing a slightly higher temperature rise then the rest and pot 5 slightly less. The additional heights of pot 1 and 6 appear to have improved heat transfer to the water.
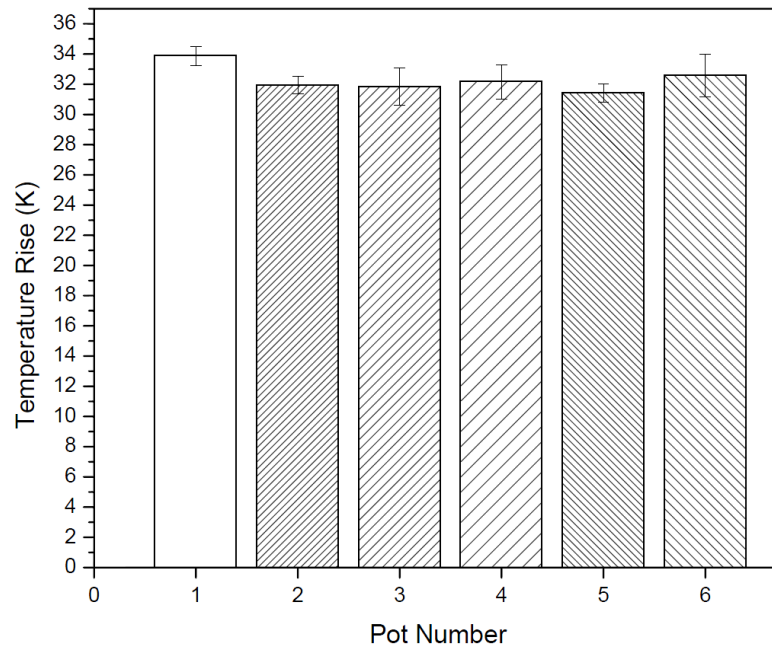
Figure 4-10: Effect of Pot Geometry and Material on Temperature Rise

4.6.   Conclusions

Biomass combustion is a very complex process with much variability inherent to

its nature but there are methods to address those concerns. By understanding the

chemical and physical reactions which are occurring during biomass combustion and the

heating of water a test protocol can be developed which allows for a task based test

while still controlling energy transfer. By adjusting the water temperature testing range

it became possible to reduce the influence of changing boiling points and variable

vaporization on the results of a test. With the addition of a simple insulative layer on

the surface of the water much of the energy from localized vaporization which does

occur can be returned to the water further reducing test variability.

Once a robust test protocol is developed it becomes possible to explore the

influence of test parameters on stove performance and test repeatability. It was found

that while some test parameters can have a significant influence on performance some do not and don't need to be controlled. The data implies that although the moisture content of the fuel has a significant effect on results, the size, geometry, and the fuel and the pot used do not. Those results would suggest that while general guidelines for fuel shape and pot geometry are useful, specific standards are not required. Any pot capable of holding the required amount of water and roughly 25cm in diameter would be expected to perform the same. The material and thickness of the pot does have the potential to change heat transfer from the stove but most readily available pots constructed of aluminum or stainless steel would seem to be acceptable. Slight variations in fuel geometry are not expected to cause significant discrepancies between tests but cut fuel should run along the wood grain and be in the range of 1-5cm in diameter. The moisture content of the fuel is parameter which needs to be standardized for test results to be comparable. While 7% moisture content was used during the parametric testing, the moisture content does not have any special significance but standardized moisture content does need to be established.

There will be times when it is necessary to make adaptations to the testing protocol. The same test procedure can be used for many testing conditions with slight modifications to accommodate the stoves to be tested. For example the mass of water to be heated may not be appropriate for some stoves. A large industrial stove will not often be heating only 5 kg of water. 5 kg of water will be appropriate for most stoves designed for family use but it is important to match the water amount to stove firepower. A stove which takes 2 hours to heat 5 kg of water was probably not designed

to be used with 5kg and 2.5kg maybe more appropriate. Stoves of different designs may also require test modifications to be made. A batch feed stove will likely not be able to adhere to restrictions of fuel geometry. During the testing of a plancha stove a pot set on the plancha surface will not represent the true heat transfer possible from the top, instead heat transfer may need to be recorded and reported in another fashion.

There are some test factors which have not be tested here such as ambient temperature and fuel species used but they are currently being considered secondary test factors. The ambient temperature of the test facility has the potential to change the combustion process and the heat transfer from the stove and body. Although the influence of ambient conditions needs to be explored it is currently being considered a secondary factor. Preliminary data testing the same stove at two different times of the year, with different ambient temperatures, had little variation in emissions production. The species of wood used is often dependent on the location of testing and may affect results, but despite the fact that physical properties of wood, such as density, vary significantly the energy content per unit mass is similar for most types of wood [54]. Data collected by the USDA found that the calorific value of 24 different tree species samples only deviated by 10.5%. When compared with a variation of 3.9% between samples of the same wood type the difference in energy content between species is insignificant. [65] Due to the similarities between wood types in calorific value and chemical composition most species would be expected to performing similarly.

There is the possibility that there will be locations which reach boiling at temperatures below 90°C but they are limited. The boiling point can be found from the

temperature when at the saturation pressure for water. The ambient barometric

pressure will change with altitude and weather conditions. The 526 mmHg barometric

pressure expected to produce a boiling temperature would occur at altitudes in the

range of 3000 meters Figure 4-11 [66]. Although this occurs the regions are limited. The

grey regions of Figure 4-12 are the locations around there world were boiling is

expected to occur below 90⁰C but the affected regions are considerably smaller than at

even 95⁰C. There will be some regions smaller then the resolution of the data also

above the 3000m elevation mark used in Figure 4-12.

The equation shown on the graph:
$$y = -3.8 \times 10^{-5}x^2 + 0.092 + 52.3$$
$$R^2 = 0.999$$
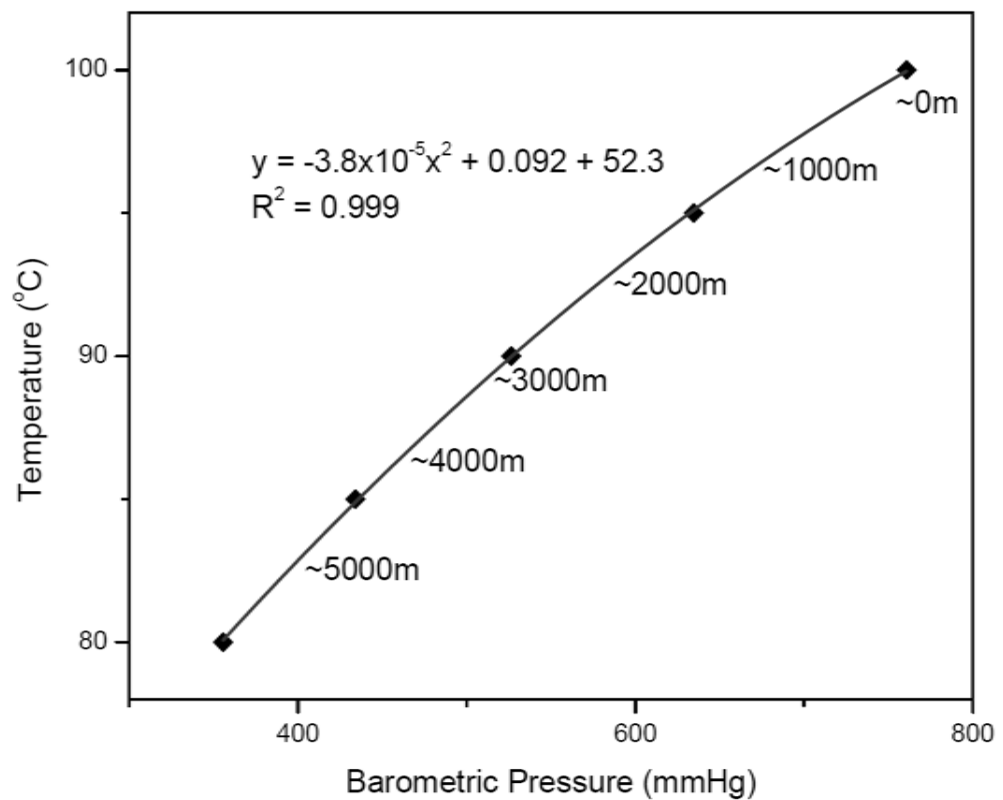
Figure 4-11: Boiling Temperature with Respect to Saturation Pressure and Estimated Elevations
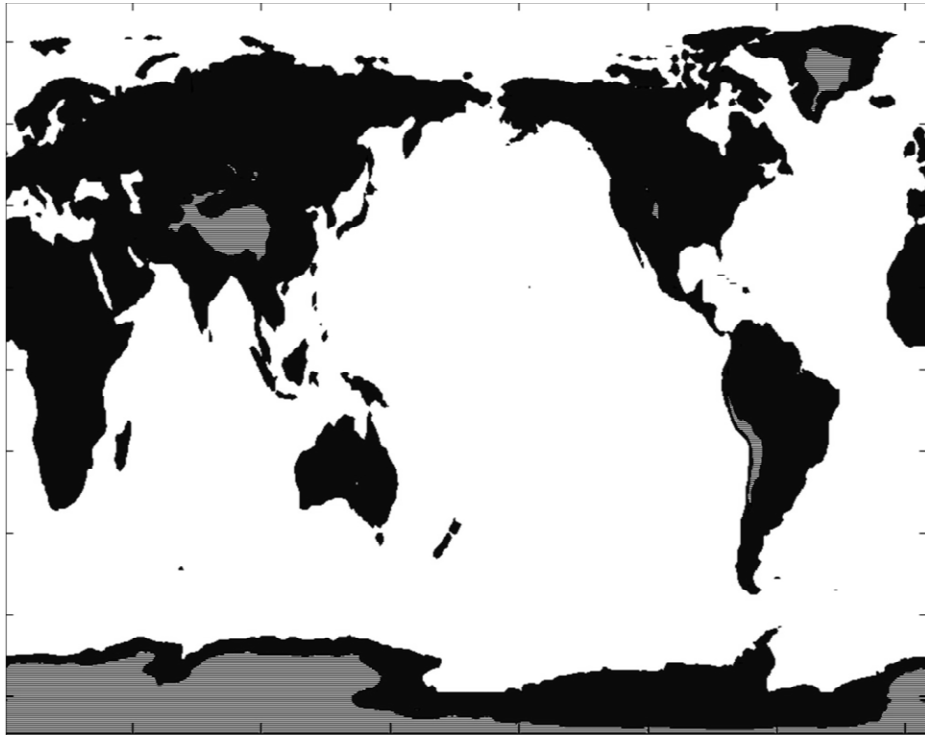
Figure 4-12: Regions Where Boiling is Expected to be Below 90⁰C [67]
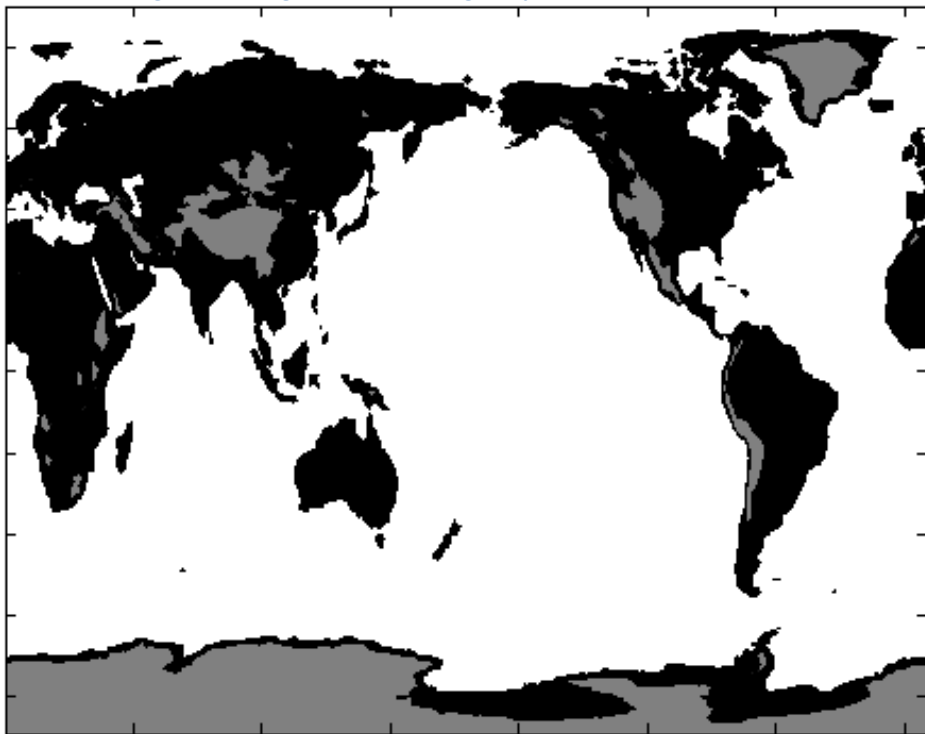
Figure 4-13: Regions Where Boiling is Expected to be Below 95⁰C [67]

5.   Particle Size Distribution and Total Exposure[3]

Wood and other biomass fuels have the potential of providing carbon neutral

energy but the products of incomplete combustion (PIC) released during combustion are

known toxins. The health consequences of the particulate matter (PM) released during

fossil fuel and tobacco combustion are well documented but wood smoke differs

considerably and the risks are not as understood [5]. The physiological effect of biomass

particle inhalation depends on the size and concentration of particles to which an

individual is exposed [67].

5.1.   Particle Formation and Deposition

The particles released from biomass combustion are damaging to the human

body. Chronic exposure to PM has been shown to double the risk of respiratory illness

and infection [2], to cause lung disease, and to permanently decrease lung functions.

The effects of PM exposure go beyond the respiratory system; exposure has been linked

to increased blood viscosity and risk of heart attack or irregular heart rhythms [68]. As

PM is inhaled into the body it acts as an immune system suppressant hindering a

person's ability to fight off infection [5] [68] through reducing the production of thymoctes

and T cells [69]. Ultrafine particles can pass through the lung-blood barrier and

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[3] Chapter is reproduction of Volckens, J. & L'Orange, C. *Particulate Matter Formation in Biomass Stoves: Influence of Stove and Cooking Pot Conditions*. To be submitted to Biomass and Bioenergy.

eventually reach organs throughout the body [68] and long term exposure may lead to an increased risk of Alzheimer's disease and brain inflammation [70].

Combustion particle formation depends on flame temperature, composition and concentration of combustion products, and residence time within the reaction zone [71]. Although PM formation is not fully understood, the process involves both nucleation and condensation mechanisms [72] [73] [59]. Nucleation is believed to initiate from the reaction of vinyl radicals with acetylene molecules to form benzene rings. These rings then grow through collision and coagulation to form stable nuclei. Cooling combustion gases condense onto these nuclei increasing their size. Oxidation occurs when a particle reacts with oxygenated molecules to form gaseous compounds [59]. The rate of oxidation is dependent on ambient gas composition and temperature. As temperature decreases the rate of oxidation slows, quenching the reaction [74]. Ideally, nucleated particles completely oxidize and no PM will leave the reaction zone but in reality smoke will often be released [59]. The size of particles formed during combustion is dependent on the amount of time spent in the formation and oxidation zones. The majority of particles from combustion are less than 1µm in diameter [5] with the mass distribution from biomass combustion typically centered on 0.17µm [75].

In addition to combustion PM, larger particles will be created from the abrasive wear of the stove and fuel. Particles up to 10µm in diameter are considered to be inhalable but deposit differently depending on their size. Deposition in the human body can be broken into three areas: the headways, the bronchial arteries, and the alveoli

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region [47]. The fraction of particles which deposit in each region of the body is shown in Figure 5-1 [76].
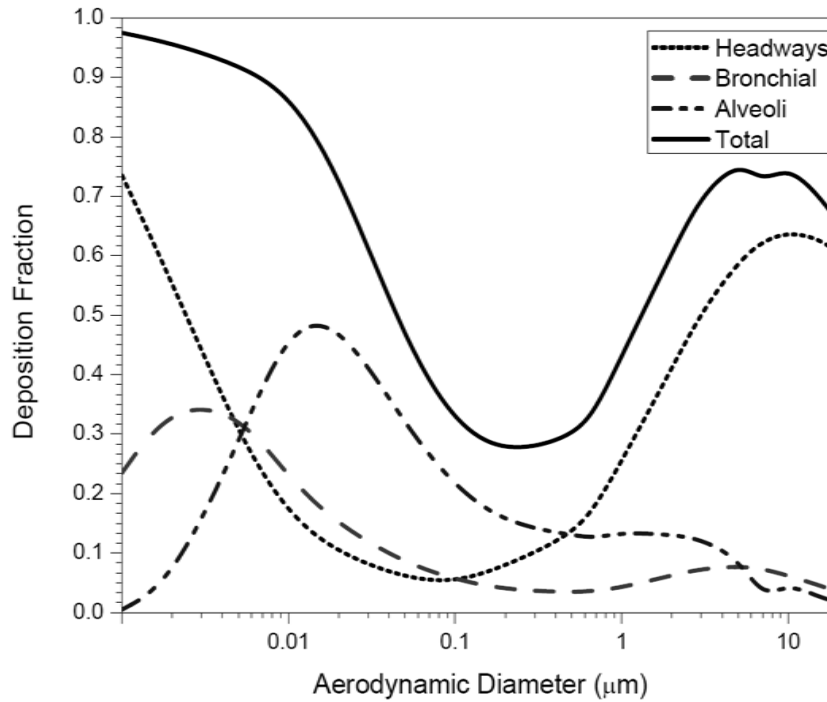
Figure 5-1: Particle Deposition Fraction in the Body Based on Aerodynamic Diameter

The health implications of inhaled particles change with their size and concentration. Previous research has focused on total mass emissions from biomass stoves [29] [23] [3] [77] with little work done on how that mass maybe distributed. In this work, we hypothesize that both wall and cooking pot temperatures affect the emissions rate and size distribution of combustion aerosol released from biomass cook stoves.

5.2.   Experimental Set-up

Tests were conducted with controlled wall and pot temperatures to isolate each of their impacts on particle formation.   Combustion efficiency was compared to PM

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mass emissions to determine how particle production changes with combustion completeness.

All tests were conducted in a 1.2mx1.2mx4.3m fume hood at the Engines and Energy Conversion Laboratory of Colorado State University. A constant displacement pump removed exhaust from the hood at $6m^3$/minute with inlet air passing through high efficiency particle air (HEPA) filters to remove background particles. Particles measurements were taken from cascade impactor and gravimetric filter systems operating in parallel. A Nano-MOUDI cascade impactor from MSP was used to separate particles into 13 size ranges from 0.01 to 10 μm. A URG-2000-30ENB cyclone and filter pack measured the mass of particles 10μm in diameter and smaller (PM_{10}). Each system was equipped with a vacuum pump and mass flow controller.

Sampling bias occurs when particles are lost during sampling. Large particles are at risk of impaction with diffusion a greater concern for small particles. Sampling line designs was restricted by the equipment used but efforts were made to minimize any potential loss. Sampling lines were kept short and straight with large cross-sectional areas whenever possible. The percentage of particles expected to be lost in the sampling line of the cascade impactor is shown in Figure 5-2 [47]. The cyclone sampling line was short with no bends and resulted in less than 4% of particles of any size being lost.
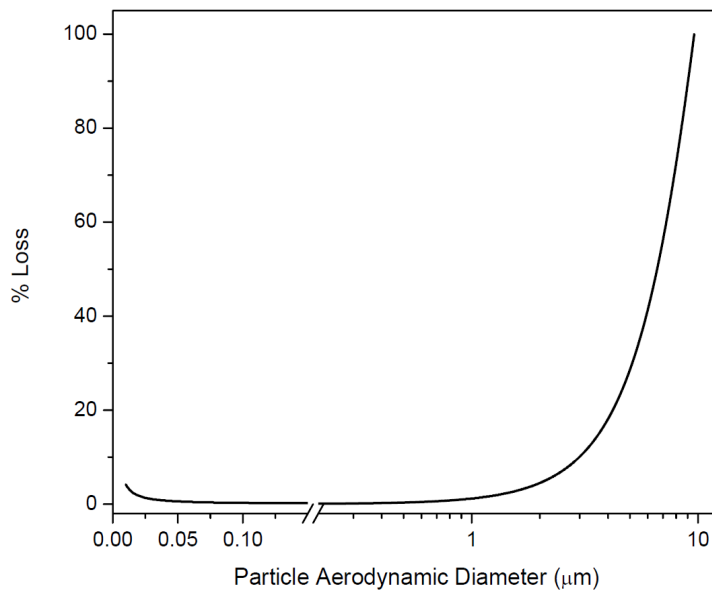
Figure 5-2: Losses in Sampling Line Leading to Cascade Impactor

5.3. Test Plan

Two test procedures were followed: variable and constant water temperatures.

The variable temperature test heated 5 kg of water from 15 °C to 90 °C and then held

that final temperature until a total of 90 minutes had elapsed. The constant water

temperature procedure started with 5 kg of water at one of two temperatures, either

0°C or a full boil (approximately 95.5°C in Fort Collins) for 90 minutes. With the

exception of one, all tests were conducted on single pot cook stoves burning 7%

moisture content (dry basis) Douglas fir. The exception was a gasifier stove burning

commercially produced wood pellets. A Fourier Transform Infrared Spectrometer (FT-

IR) or a Testo electrochemical analyzer was used to monitor carbon monoxide (CO)

during each test as a real time indication of stove performance. The test matrix

followed and the number of replicates performed is shown in Table 5.1. The total mass

emissions of each of the tests with the standard deviation between replicates can be found in Figure 5-8.

Table 5.1: Particulate Matter Mass Distribution Test Matrix

Stove	Variable Water Temperature	Constant Water - Cold	Constant Water - Hot
Ceramic	2	x	x
Metal	2	2	2
Water Cooled	2	x	x
Gasifier	2	x	x

5.3.1. Size Distributions

5.3.1.1. Stove Comparison

Two stoves of similar design but constructed of different materials were used as baseline conditions. The stoves were selected due to their similarity to improved stoves currently being sold in developing countries. Traditional stoves may perform differently than the baseline conditions but trends are expected to be similar.

5.3.1.2. Stove Wall Temperatures

The temperature of the stove wall likely affects the particles being released by changing the combustion region and/or inducing thermophoresis. Lowering the temperature inside the stove should reduce oxidation resulting in a greater number of large particles. Thermophoresis occurs due to thermal gradients which pull particles towards the colder surface on which they are deposited. Small particles are preferentially affected by thermophoresis [14] shifting the count distribution towards larger ones. A double walled metal stove with ice water circulating inside, capable of keeping the stove at a constant temperature, was tested to determine the effect of wall

temperature on PM production. The stove used during the cold stove wall tests can be found in Figure 5-3.
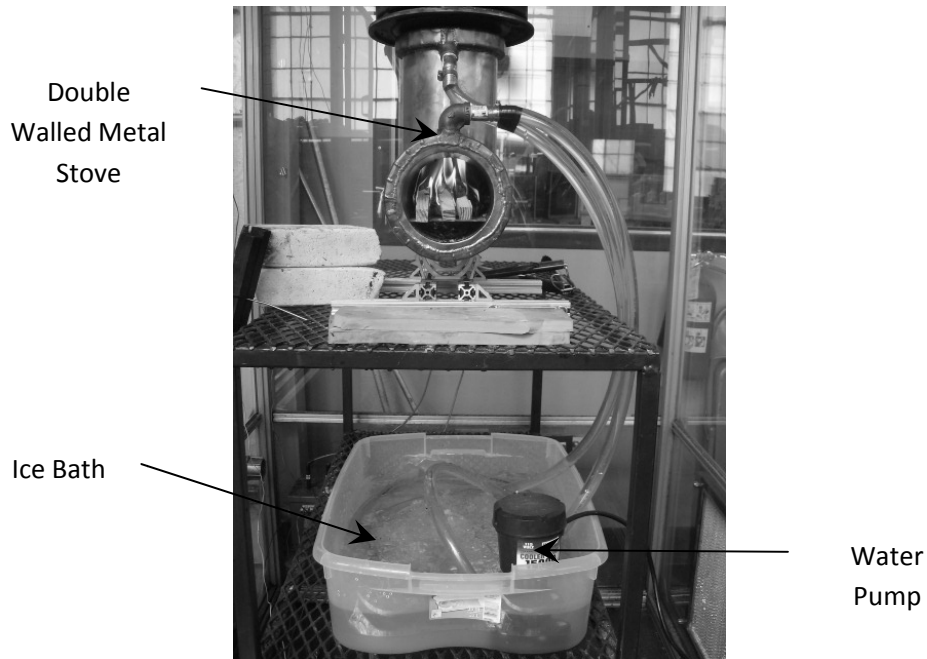
Figure 5-3: Cold Walled Stove

5.3.1.3. Pot Temperature

Tests were conducted to determine how cooking pot temperatures affect particle size distribution. Pot temperatures change with cooking time and practice and may alter particle production. If changes are seen they are not expected to be as significant as those with changing wall temperatures.   Variations in the temperature of a cooking pot are small compared to those of the gas stream or stove wall; these larger fluctuations will likely dominate any changes found. Tests were conducted with the cooking pot kept ice cold and then repeated at a full boil.

5.3.1.4. Wood Pellets

A gasifier stove was tested to see how the combustion zones affect particle mass distribution. In a gasifier the pyrolysis and ignition zones are separated

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which may affect the particles released. Slight modifications were made to the test procedure to accommodate the gasifier stove. These variations included being ignited with kerosene instead of wood and having the cooking pot off the stove when started. The gasifier also used batch feeding instead of the continuous feeding possible with other stoves.

5.3.2. Total PM Production

Room particle concentration has a significant impact on diminished health from PM exposure. Correlations have been found between biomass combustion efficiency and PM production [78] but we hypothesize factors beyond combustion influence the particles released. This can be established if different stoves can achieve the same combustion efficiency while consistently having different PM production rates. Modified combustion efficiency (MCE) was used to correlate PM production to the combustion process. MCE is calculated from equation 10 where the delta (Δ) is the molar concentration above ambient conditions. Nine stoves were tested under high and low power conditions. The high power test heated 5 kg of water from 15°C to 90°C. The low power tests maintained 5 kg of water at 90°C for 45 minutes.

$$MCE = \frac{\Delta CO_2}{\Delta CO_2 + \Delta CO} \qquad [10]$$

5.4. Results and Discussions

5.4.1. Stove Comparisons

The baseline stove size distributions can be found in Figure 5-4. The metal stove had lower overall emissions and a more balanced size distribution then that seen with the ceramic stove. Although the two distributions appear to have significant differences

the impactor cutpoints need to be considered. A theoretical cut point exists at 0.171μm which differs by only 0.001μm from the predicted mass median diameter found by Dasch [75]. Slight variations in the volumetric flow rate could change the impactors cut points. When tests were compared against the baseline conditions both particle distributions in Figure 5-4 were considered.
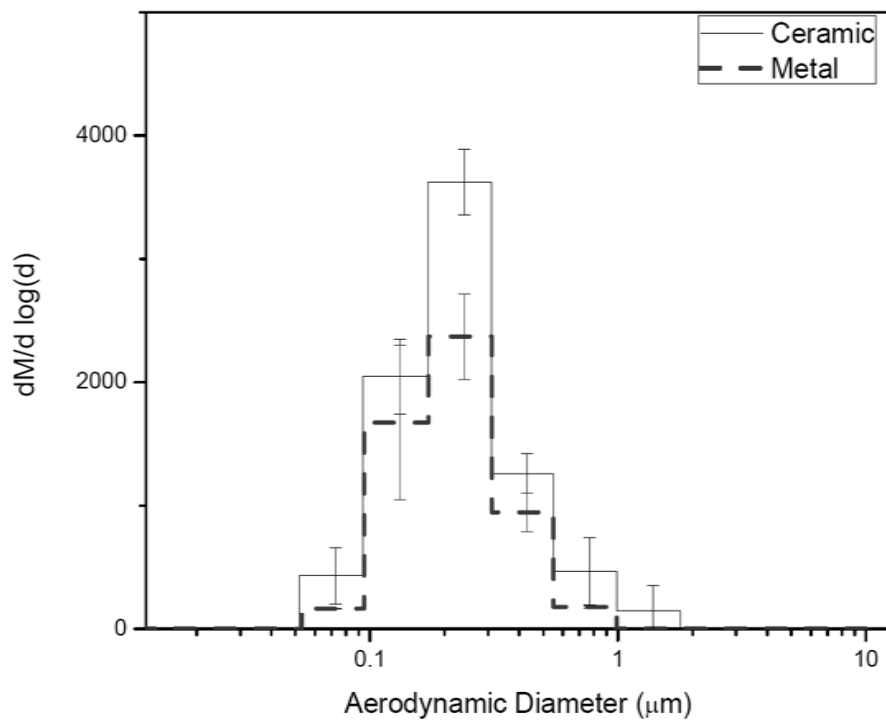
Figure 5-4: Mass Distribution of Two Baseline Condition Biomass Stoves

5.4.2. Stove Wall Temperatures

Lowering the stove wall temperatures had little impact on particle distribution or production. An ice cold wall increased the mass fraction of large particles but had little change on total production. The changes seen were insignificant compared to the variations seen between the baseline stoves. The effects of thermophoresis could not be determined as particles gathered on condensed water on the stove walls.
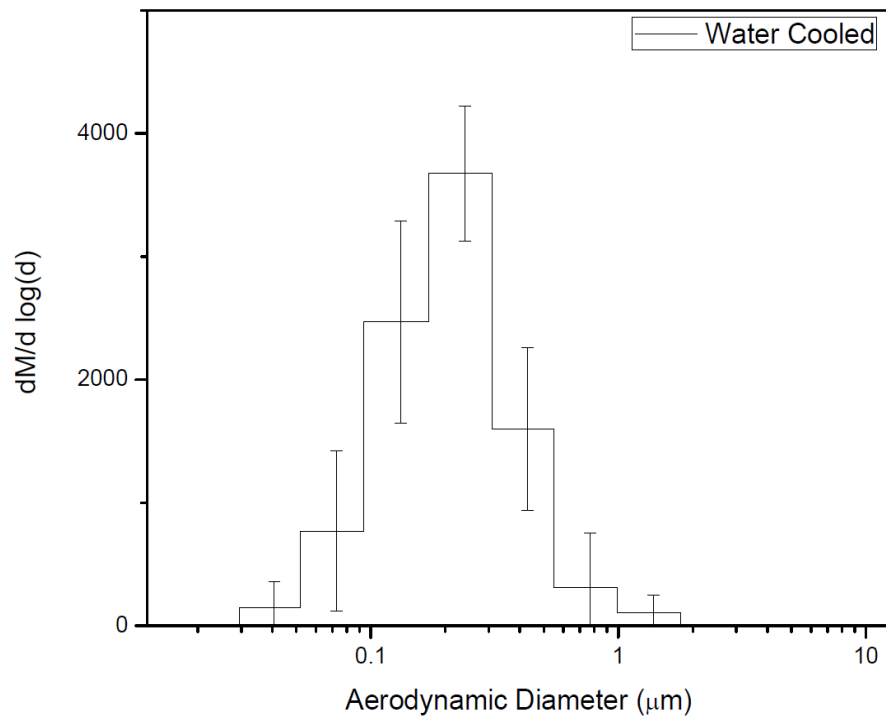
Figure 5-5: Mass Distribution of Water Cooled Biomass Stove

5.4.3. Pot Temperatures

Contrary to initial assumptions, the cooking pot temperature has significant impact on PM formation. The hot pot (full boil) and cold pot (ice water) tests, Figure 5-6(a) and (b) respectively, had different total mass productions and size distributions from each other and from the baseline conditions. Particles smaller than found in previous tests and a reduced total PM production were found when using a hot pot. Cold pot testing saw similar total particulate emissions but had a distribution shifted slightly towards large particles.
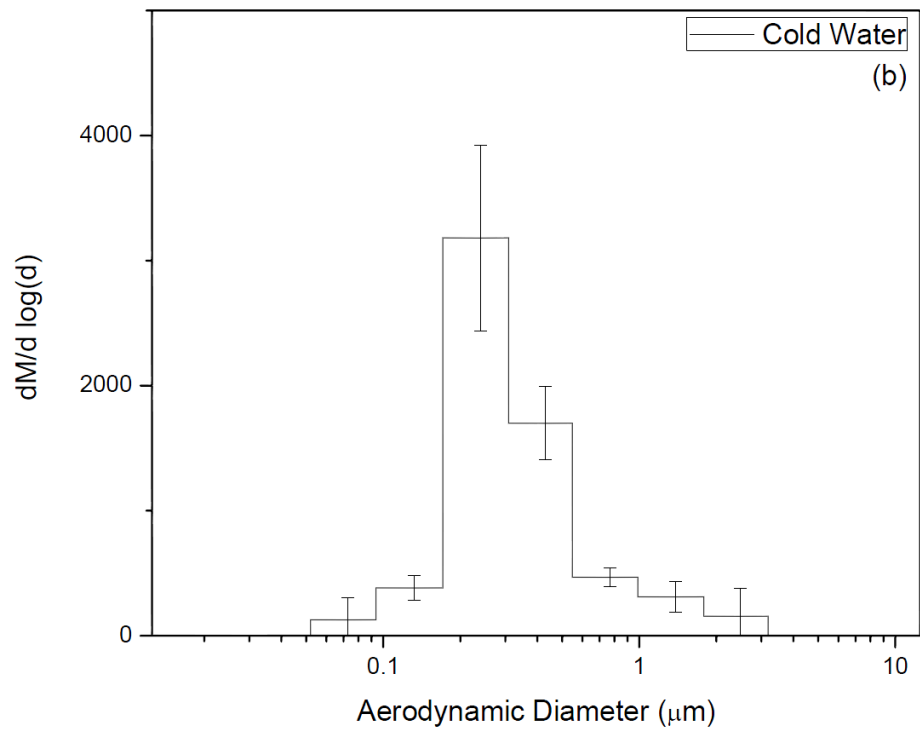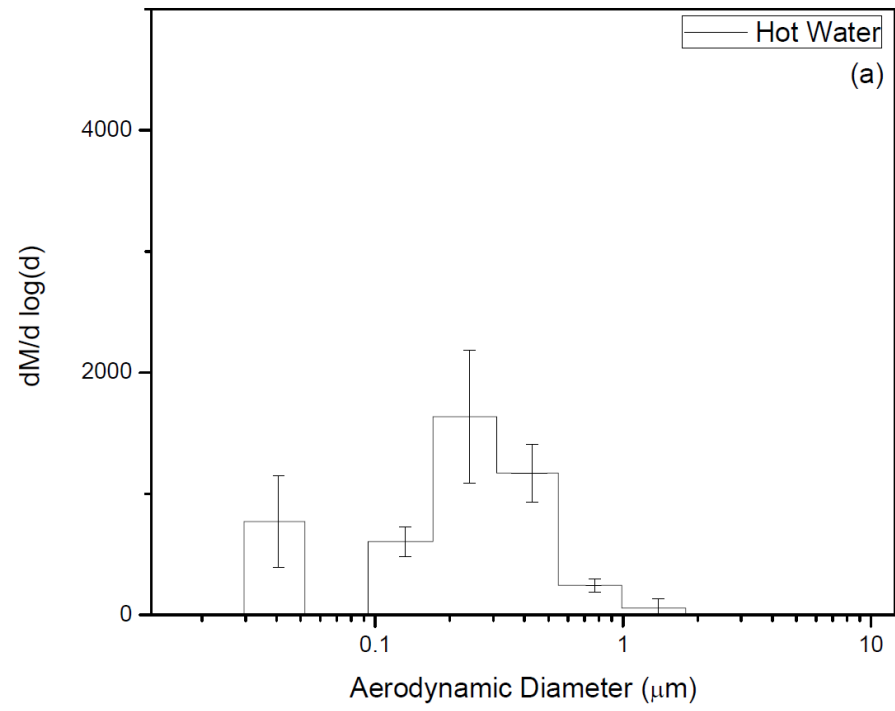
Figure 5-6: Constant Water Temperature Size Distribution – Hot Pot (a), Cold Pot (b)

5.4.4. Wood Pellets

Gasifier stoves are traditionally thought to have lower than average emissions but this was not evident from the PM distribution Particles produced from the gasifier stove covered a considerably wider size range and had high total mass production. The gasifier stove also had larger than average uncertainty. With the high level of uncertainty it becomes difficult to determine total production but the wider distribution appears to be consistent between repetitions. Wood pellets typically contain a large percentage of inorganic material from wood bark which may explain the wide distribution. Hasler has found that combustion of a wood and bark mix produces bimodal distributions with the second maximum on 5μm [79].
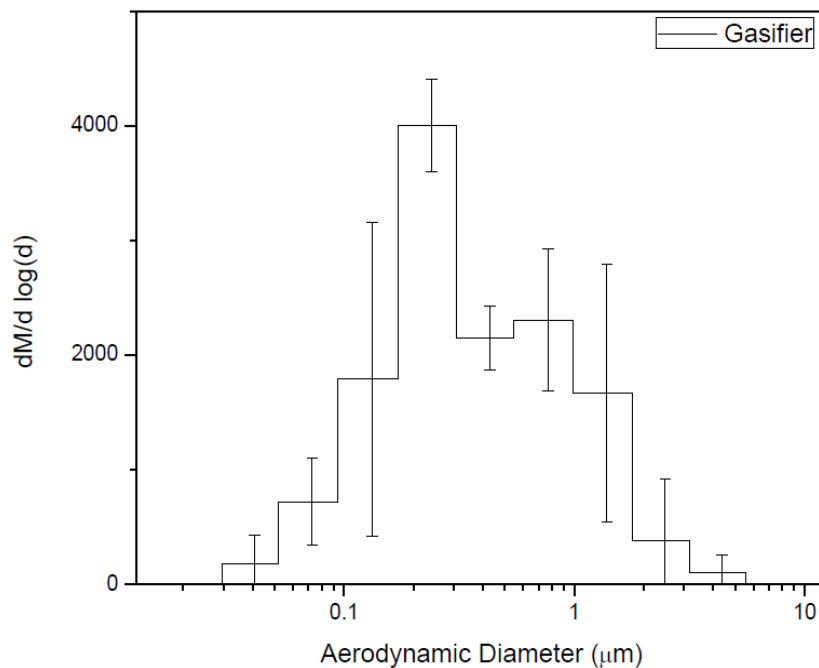
Figure 5-7: Mass Distribution of Gasifier Stove Running on Commercial Wood Pellets
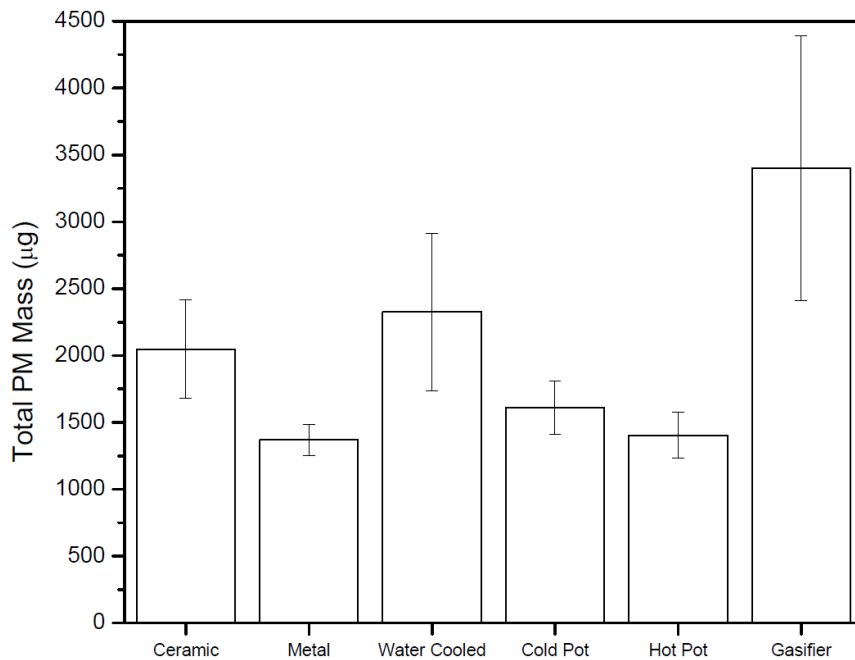
Figure 5-8: Total Particulate Mass Collected

5.4.5. Total PM Production

Emissions factors (EF) were used to compare PM_{10} production. EFs are calculated by normalizing the total PM_{10} emissions by fuel use. Correlation was found between MCE and EF under both high power and low power testing conditions. Both conditions had similar trends with high power testing showing a slightly steeper EF/MCE slope. Two stoves have been singled out for comparison in Figure 5-9. The ceramic and water cooled stoves are the same used during the particle distribution tests. Both stoves had similar trends but had different EFs at the same MCE. The two stoves also perform differently between high and low power testing. Despite the fact that stoves follow similar combustion efficiency trends there are obviously factors beyond the combustion processes affecting PM production.

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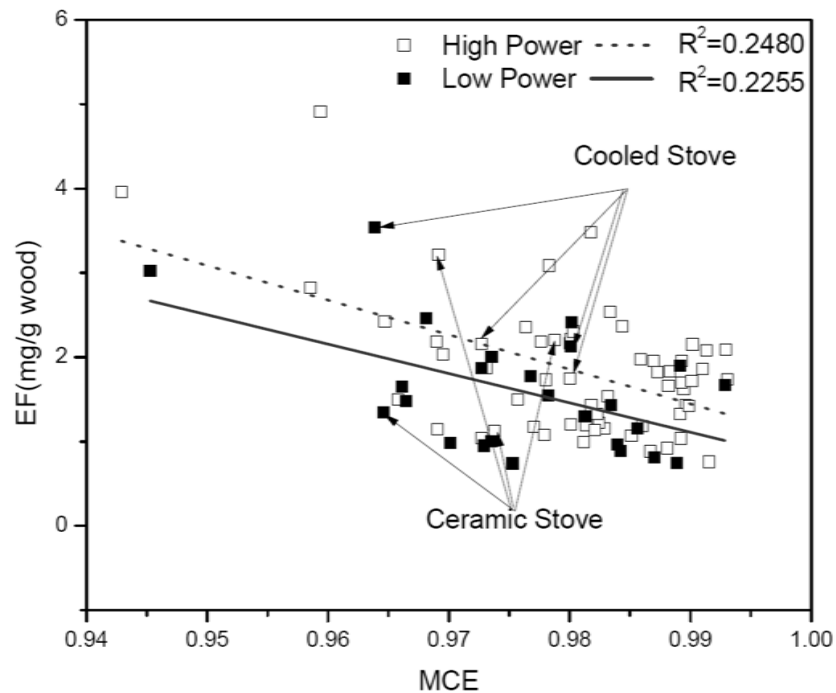
Figure 5-9: PM Production vs Modified Combustion Efficiency

5.5. Conclusions

The health effects of inhaled biomass particles depend on their size and

concentration.   Although the fraction of particles which deposit in the inhalable and

thoracic regions from combustion doesn't change significantly, repairable deposition

has a much larger variation. Variation in size distribution has implications beyond purely

the diameter of the particles. As the size of particles change, the number of particles

required to achieve a given mass will also change. Taking the constant pot temperature

tests as an example, both distributions had similar total mass production but would

have very different particle concentrations. To achieve the same mass as one of the

3µm particles from the cold pot it would take it would take a million 0.03µm particles

from the hot pot. This implies the large mass of small particles in the hot pot test is

especially worrisome, as the hot pot test would have had many more particles available to be inhaled and deposited compared to the cold test.

Despite slight variations the ceramic, metal, and cooled stove all exhibited similar distributions and production. The surface material and the temperature of the stove body have some influence on particle distribution but appear to be insignificant compared to the effects of pot temperature. The large influence of pot temperature is likely due to the amount of surface contact it has with the gas path. The gas path in the stove flows mostly parallel to the stove walls resulting in very little contact with the pot surface. Changing the temperatures of the walls and cooking pot may also be altering the particulate formation process through changes in the oxidation and formation regions of the stove.

The broader distribution seen with the gasifier stove is likely due to the high fraction of bark in the wood pellets but the effects of the reaction zone locations cannot yet be ruled out. Hasler's work with wood and wood bark combustion had similar wide particle distributions to that seen in the gasifer test [79]. Additional gasifier stove tests should be performed using wood chips made from the same Douglas fir as the other tests and with other gasifier models to isolate factors.

The high fraction of large particles lost in the sampling line was initially thought unimportant because of combustion particle size but this assumption was not accurate. A significant mass of particles were found to be above 1μm during some tests and were likely lost. The gasifier, cold pot, and baseline stoves should be repeated with an improved sampling system to see the total contribution of large particles.

MCE trends with PM in biomass stoves but is not the sole factor in production rate. If stoves can achieve the same combustion efficiency it is reasonable to say the reaction zones are similar between tests. If the combustion zone is the same but differences in PM production are seen they are likely due to conditions other places in the stove. Further research to determine why EFs do not go to zero as MCE goes to one may yield interesting results to how particles form in biomass cook stoves.

The variations seen between stove models are not significant but pot temperature is. This implies that it is reasonable to assume that most stoves, which fall within the range tested here, will have similar PM mass distributions but that distribution is changing throughout the cooking task. The differences seen between cooking practices will likely be greater than between stove models.

6.   Summary and Conclusions

Over 3 billion people use the most basic energy source available on a daily basis with devastation health effects. The need for improved cook stoves in undeniable and many very talented groups are working on solving the problem but collaboration is still difficult. Communication and cooperation is improving but groups are still hampered by the fact that data cannot be shared with any degree of confidence. The standards currently in place each have their own desirable elements but they fail to provide enough detail to the test to have comparable results.

A test methodology which follows an energy transfer criteria instead of being purely task based allows for more control and repeatability. By reducing the variability from water vaporization using a changed test temperature range, and introducing insulation makes it easier to ensure that all biomass cooks stove tested, regardless of location, are undergoing the same procedure. With a more robust test standard it become possible to start exploring what test factors have a large influence on the results and need to be controlled to get comparable results. The majority of test parameters tested did not have a significant impact. There are advantages to having conditions falling within a range and a single rigid test condition is most likely not required. Of the factors tested fuel moisture content seemed to be the parameter which requires the strictest control. No suggestion has been made here about what

moisture content should be used, it is a question which should be discussed between interested parties, but a decision should be made.

There are some conditions which were not explored here but will be tested if this new protocol is adopted. This new test standard was designed with use around the world in mind but this does need to be validated. Initial beliefs are that variations in ambient conditions or in the fuel used will not greatly influence results but field testing will be the best way to test this. For the new test standard to be of any use it must not only decrease variability but must be accepted by the larger stove community. Perhaps the best validation of the new test standard protocol is having different groups following the same protocol using the same stove model but testing in local ambient conditions and using locally available fuel.

Using the new test standard it become possible to begin exploring how stove and testing conditions affect the emissions released. Test standards only regulate the total mass of particles despite the fact that human response to exposure is also dependent on particle size and concentration. Contrary to initial belief, the conditions of a pot have a much greater influence on particle size distribution than stove conditions. The contact the gas has with the pot is much greater than with the stove body.

The large fraction of particles which may have been lost in the cascade impactor sampling line makes it important to repeat some of the mass distribution tests with an improved system. The vast majority of combustion particles should have successfully

been sampled but the larger particles, which are still capable of being inhaled, was likely lost.

There is still significant uncertainty associated with results of the biomass cook stove test standard. The variability of the user contributes significant uncertainty to the test. There have been attempts to limit these effects but most have been impractical or produced unrealistic results. The variability is unfortunate but the user is a necessary component of the test. Invaluable data is gathered from the tester's impressions and observations during a test.

Only two or three replicates were performed for each test which is significantly lower than good statistical practice calls for. Conducting more test replicates would reduce the level of certainty. To determine the feasibility of achieving the number of replicates required to have confidence statistical power was used. Statistical power calculations can be used to establish if two tests are statistically different when small sample sizes are available. The number of test replicates required can be calculated from Equation 11.

$$n = \frac{2\left(Z_{1-\alpha/2} + Z_{1-\beta}\right)^2}{\left(\frac{\Delta\mu}{\sigma}\right)^2} \tag{11}$$

Where:

n: number of samples required

α: Type 1 error, probability of rejecting the null hypothesis when it is true

β: Type 2 error, probability of not rejection null hypothesis when it is false

Δμ: variation in means between sample and null hypothesis

σ: standard deviation

α and β are inversely proportional to the number of test replicates required to achieve statistical significance. By minimizing these values the probability of inaccurately judging the truth of the null hypothesis is reduced. Each term has an associated critical Z value which is a measure of the number of standard deviations away from the mean value a point is. The Z value gives an indication of what percentage of the data a measurement is capturing. As the population standard deviation is unknown the standard deviation of a sample can be used to determine the required number of test replicates to be conducted [81]. The detection range and standard deviation can be normalized by the mean before being used in Equation 11.

If there is to be any statistical confidence in testing biomass cooks stoves the variation between replicates must be reduced. Any reduction which can be in test variability will drastically reduce the number of test replicates to be conducted. The number of test replicates changes with the square of the standard deviation. Even though each of the changes to the protocol may only reduce variability by a small fraction collectively they drastically reduce the required number replicates.

A coefficient of variation of 18% was used based on the average variation seen during the parametric tests. Exploring the larger cook stove data set which has been collected at the Engines and Energy Conversion Laboratory this value could be dropped when considering CO but is a reasonable value to use with particulate matter testing. If only carbon monoxide or wood use is to be judged as few as 4 test replicates may

suffice. As an initial value detecting differences of 25% was used. An α value of 0.05 and a β of 0.1 were chosen based on convention. Using these values in Equation 11 8-9 replicates are required.

The two or three test replicates used during testing do not result in high statistical confidence. When data is being taken as part of initial stove develop this low confidence is likely acceptable. Due to the multiple hours required to perform each test even 8 replicates is not be reasonable if done on every stove. More test replicates could however be conducted before a stove design goes to final production. With the three replicates used during the majority of the parametric study variations in the range of 40-45% could be detected which was not the case.

It is important to explore how the assumed values used in Equation 11 effect the number of test replicates to be performed. Each of the parameters was varied independently of each other and the number of test replicates was calculated. The difference between tests to be detected caused the largest variability. Detecting a variation of 25% was used as initial starting point but if a smaller difference was desired the number of test replicates would quickly become impractical. Based on Table 6.1 the initial values used are reasonable but the desired $\Delta\mu$ should be carefully considered when planning future testing.

Table 6.1: Affect of Equation Parameters on Required Test Replicates

	Variable Range	Replicate Range
α	0.01-0.1	5-10
β	0.01-0.15	5-12
σ	0.1-0.25	3-18
$\Delta\mu$	0.05-0.5	2-155

Having low statistical confidence does not mean that the results are invalid; instead it should be taken as a reason for caution when evaluating data. Confidence in the test methodology can be increased. Only a limited number of test replicates were available at the time of publishing but as the method gains more use data can be compiled to gain confidence in its validity. The need for these replicates is especially important considering the small variations seen between stove models and parameters tested.

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Appendix A – Raw Data

Parametric Study Moisture Content

	Wood Use (g)	±	Carbon Monoxide (g)	±	Particulate Matter (mg)	±
4% MC	368.6	13.2	15.9	0.9	1287.5	132.2
7% MC	328.4	27.7	14.9	4.2	1058.3	139.1
13% MC	370.0	3.7	8.8	0.4	933.5	286.4
30% MC	386.2	25.0	14.6	1.6	1070.0	135.2

Parametric Study Wood Size

	Wood Use (g)	±	Carbon Monoxide (g)	±	Particulate Matter (mg)	±
Small	342.7	21.0	14.2	5.3	1997.5	736.1
Medium	328.4	27.7	14.9	4.2	1192.3	257.9
Large	345.4	37.1	12.4	4.7	1322.7	519.3

Parametric Study Pot Geometry

Pot #	Starting Temperature (K)	Ending Temperature (K)	Temperature Change	±	Propane Used (g)	±
1	287.3	321.2	33.9	0.7	23.3	0.6
2	288.2	320.1	31.9	0.6	23.3	0.6
3	288.0	319.8	31.8	1.3	22.0	1.0
4	287.6	319.7	32.2	1.1	23.0	1.0
5	289.0	320.4	31.4	0.6	23.2	0.7
6	289.8	322.4	32.6	1.4	22.7	1.5

Parametric Study Effects of Insulation

Insulation						
Initial Temperature (K)	Starting Weight (g)	Ending Weight (g)	Temperature Change	Water Vaporized (g)	±	Mass Gain of Foam (g)
14.7	5000.0	4956.0	75.3	44.0		61
14.5	5000.0	4955.0	75.5	45.0	9.5	8
14.7	5000.0	4972.0	75.3	28.0		23
No Insulation						
Initial Temperature (K)	Starting Weight (g)	Ending Weight (g)	Temperature Change	Water Vaporized (g)	±	Mass Gain of Foam (g)
14.1	5000.0	4844.0	75.9	156.0		x
14.8	5000.0	4866.0	75.2	134.0	16.8	x
15.9	5000.0	4877.0	74.1	123.0		x

Cascade Impactor after Accounting for LOQ

Stage Midpoint (µm)	Substrate Mass Gain (µg)					
	B1100 (Ceramic)	Gasifier	Ice Water	Hot Water	Gen 3 (Metal)	Waterjacket (Cooled)
7.786	0.0	0.0	0.0	0.0	0.0	0.0
4.386	0.0	211.9	0.0	0.0	0.0	0.0
2.486	0.0	759.0	311.8	0.0	0.0	0.0
1.387	289.9	2467.0	223.9	0.0	0.0	205.8
0.768	658.3	1872.0	415.8	203.4	183.8	627.0
0.429	1373.8	2343.1	1905.3	1001.5	1057.8	1130.1
0.240	3813.2	4288.1	3708.1	2345.8	2125.2	3287.8
0.132	2262.0	2757.0	313.8	1116.3	2117.8	1885.6
0.073	591.8	993.2	0.0	0.0	165.5	308.9
0.041	0.0	353.3	0.0	1339.9	0.0	0.0
0.023	0.0	0.0	0.0	0.0	0.0	0.0
0.013	0.0	0.0	0.0	0.0	0.0	0.0

Stove Mode	Version #	Test Date	FoM	Tot/Twood	Azel	AceN/wood	HS MCE	-E PM/(wood)	DCWsoc
Gen 2	Gen2 SP v7	1/11/2008	0.15	5.04E-03	0.26	5.21E-03	0.97	0.21	4.19E-02
Gen 3	Gen3 SP v7	1/15/2008	0.10	2.77E-03	0.10	2.95E-03	0.98	2.30	2.03E-02
Yue Xiang	YXv1	1/28/2008	0.11	4.52E-03	0.05	2.00E-03	0.96	4.01	4.07E-02
Yue Xiang	YXv1	1/30/2008	0.08	3.52E-03	0.08	2.53E-03	0.94	3.90	6.30E-02
Yue Xiang	YXv2	2/28/2008	0.08	2.25E-03	0.08	2.30E-03	0.98	2.15	1.99E-02
Yue Xiang	YXv2	2/29/2008	0.11	2.48E-03	0.12	2.66E-03	0.98	1.72	2.01E-02
Grey Hsii Kit	Hsii	3/10/2008	0.07	2.10E-03	0.08	2.24E-03	0.98	2.08	1.66E-02
Insulated RF		3/10/2008	0.11	2.66E-03	0.10	2.39E-03	0.98	1.11	2.86E-02
Insulated RC		3/11/2008	0.08	1.52E-03	0.09	1.84E-03	0.97	1.14	4.26E-02
Uninsulated RE		3/21/2008	0.14	2.41E-03	0.14	2.41E-03	0.99	0.02	2.00E-02
Water Jacket RC		3/24/2008	0.30	6.37E-03	0.20	4.31E-03	0.98	2.21	3.88E-02
Water Jacket RE		3/24/2008	0.36	6.50E-03	0.25	4.51E-03	0.97	2.00	5.06E-02
G2100	1	4/7/2008	0.14	2.48E-03	0.17	2.98E-03	0.98	2.18	5.14E-02
S2100	1	4/8/2008	0.11	2.73E-03	0.15	3.01E-03	0.99	1.00	2.27E-02
S2100	1	5/20/2008	0.12	2.82E-03	0.09	2.16E-03	0.99	1.96	1.80E-02
Gen2 Dbl Pot	Gen2DPv2	2/18/2008			0.20	4.40E-03	0.96	2.42	4.94E-02
Gen2 Dbl Pot	Gen2DPv2	2/19/2008	0.25	4.69E-03	0.15	2.66E-03	0.98	1.83	1.86E-02
Gen2 Dbl Pot	Gen2DPv3	2/22/2008	0.19	3.72E-03	0.17	2.81E-03	0.98	1.75	3.41E-02
Gen2 Dbl Pot	Gen2DPv3	2/25/2008	0.13	2.01E-03	0.12	1.80E-03	0.88	3.18	4.19E-02
Gen2 Dbl Pot	Gen2DPv3	3/3/2008	0.25	2.01E-03	0.15	2.21E-03	0.98	1.49	4.28E-02
Gen2 Dbl Pot	Gen2DPv4	3/7/2008	0.25	2.49E-03	0.17	2.40E-03	0.99	1.42	1.60E-02
Gen2 Dbl Pot	Gen2DPv4	3/21/2008	0.15	1.98E-03	0.14	1.78E-03	0.99	1.04	2.66E-02
Gen2 Dbl Pot w/Chimney	Gen2DPv5	4/7/2008	0.13	2.62E-03	0.13	2.61E-03	0.99	1.97	2.29E-02
Gen2 Dbl Pot w/Chimney	Gen2DPv5	4/7/2008	0.17	3.17E-03	0.16	2.97E-03	0.98	3.09	4.02E-02
S4100 Certification Test 1	1	10/22/2008	0.15	2.97E-03	0.15	2.49E-03	0.99	1.74	1.35E-02
S4100 Certification Test 2	1	10/22/2008							

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Stove Model	Version	TestDate	HCN	HCNwood?	MsH Car?	Methanewood	Form H	Form/sooc	Acet
Gen 2	Gen2 SP v7	4/11/2008	0.04	1.71E-03	0.75	0.03	0.10	4.06E-03	0.07
Gen 2	Gen2 SP v7	1/15/2008	0.00	1.04E-03	0.60	0.02	0.07	2.20E-03	0.00
Yue Xiang	YXv1	1/20/2008	0.08	3.99E-03	0.63	0.03	0.07	3.25E-03	0.04
Yue Xiang	YXv1	1/30/2008	0.13	6.40E-03	1.09	0.05	0.11	6.20E-03	0.06
Yue Xiang	YXv2	2/20/2008	0.00	1.23E-05	0.92	0.03	0.05	1.55E-03	0.06
Yue Xiang	YXv2	2/29/2008	0.02	5.06E-04	0.62	0.02	0.00	2.51E-03	0.07
Grey RSH RE	RSH	3/10/2008	0.01	3.19E-04	0.37	0.02	0.04	1.81E-03	0.04
Insulated RF		3/10/2008	0.01	3.82E-04	0.48	0.01	0.03	2.20E-03	0.08
Insulated RE		3/11/2008			0.60	0.01	0.10	2.10E-03	0.09
Uninsulated RE		3/21/2008			1.51	0.02	0.14	2.97E-03	0.14
Water Jacket HE		3/24/2008	0.05	8.10E-04	1.14	0.02	0.44	7.84E-03	0.20
Water Jacket RF		3/24/2008	0.04	7.40E-04	0.86	0.02	0.36	6.17E-03	0.26
S2100	1	4/7/2008	0.03	6.54E-04	0.71	0.02	0.13	2.51E-03	0.15
S2100	1	4/9/2008	0.02	6.56E-04	0.34	0.01	0.08	2.68E-03	0.09
S2100	1	5/20/2008	0.00	3.00E-05	0.38	0.01	0.07	2.14E-03	0.00
Gen2 Dbl Pot	Gen2DPv2	2/18/2008	0.10	3.16E-03	1.34	0.04	0.16		0.16
Gen2 Dbl Pot	Gen2DPv2	2/12/2008	0.05	1.55E-03	0.71	0.02	0.11	3.76E-03	0.00
Gen2 Dbl Pot	Gen2DPv3	2/22/2008	0.07	1.89E-03	2.30		0.19	5.35E-03	0.09
Gen2 Dbl Pot	Gen2DPv3	2/26/2008	0.05	1.40E-03					0.06
Gen2 Dbl Pot	Gen2DPv3	3/3/2008	0.03	4.70E-04	1.01	0.02	0.11	2.00E-03	0.12
Gen2 Dbl Pot	Gen2DPv4	3/7/2008	0.00	5.70E-04	0.50	0.01	0.11	2.55E-03	0.00
Gen2 Dbl Pot	Gen2DPv4	3/21/2008	0.01	2.79E-04	0.50	0.01	0.08	1.53E-03	0.08
Gen2 Dbl Pot w/Chimney	Gen2DPv5	4/7/2008	0.04	1.00E-03	0.60	0.02	0.10	2.65E-03	0.10
Gen2 Dbl Pot w/Chimney	Gen2DPv5	4/7/2008	0.10	3.13E-03	1.02	0.03	0.18	5.73E-03	0.11
S4100 Certification Test 1	1	10/22/2008	0.01	2.15E-04	0.31	0.01	0.07	1.70E-03	0.10
S4100 Certification Test 2	1	10/22/2008							

Stove Model	Version	TestDate	FoodMethane	SH MCE	HE (MJ/kgCO2)	CO2/kcal	HCl	FoodHCN	Metals
Gen 2	Gen2 DP v7	1/11/2008	2.98E-03	0.97	1.87	2.61E-01	0.03	9.30E-05	0.92
Gen 2	Gen2 SP v7	1/15/2008	2.00E-03	0.99	1.70	2.01E-01	0.03	9.55E-05	0.05
Yue Xiang	YXv1	1/20/2008	1.98E-03	0.97	2.00	3.10E-01	0.02	9.15E-05	0.49
Yue Xiang	YXv1	1/30/2008	2.78E-03	0.97	1.48	2.92E-01	0.03	1.31E-04	0.78
Yue Xiang	YXv2	2/20/2008	2.06E-03	0.98	0.96	2.16E-01	0.00	5.76E-08	1.13
Yue Xiang	YXv2	2/29/2008	2.23E-03	0.99	1.00	1.01E-01	0.01	0.00E-05	0.77
Grey RGHI RL	18.11	3/10/2008	1.84E-03	0.98	1.55	3.29E-01	0.01	2.22E-05	0.08
Insulated RF		3/10/2008	2.22E-03	0.97	1.66	3.29E-01	0.01	3.89E-05	0.62
Insulated RE		3/11/2008	2.00E-03						0.47
Uninsulated RE		3/21/2008	2.04E-03	0.99	0.75	1.00E-01	0.04	8.74E-05	1.07
Water Jacket RE		3/24/2008	3.02E-03	0.98	2.13	4.10E-01		6.83E-05	0.93
Water Jacket RF		3/24/2008	4.28E-03	0.96	3.64	6.89E-01	0.03	6.83E-05	0.84
S2100	1	4/7/2008	3.33E-03	0.97	1.66	3.49E-01	0.02	6.08E-05	0.64
S2100	1	4/9/2008	3.20E-03	0.96	1.35	6.02E-01	0.02	5.59E-05	0.47
S2100	1	5/20/2008	1.85E-03	0.98	2.41	2.47E-01		0.00E+00	0.40
Gen2 Dbl Pot	Gen2DPv2	2/18/2008	6.17E-03	0.97	0.99	4.80E-01	0.03	7.38E-05	1.23
Gen2 Dbl Pot	Gen2DPv2	2/12/2008	2.52E-01	0.97	2.47	4.91E-01	0.07	1.52E-04	0.99
Gen2 Dbl Pot	Gen2DPv3	2/22/2008	2.44E-03	0.98	0.74	4.02E-01	0.02	4.39E-05	1.93
Gen2 Dbl Pot	Gen2DPv3	2/26/2008	1.03E-03	0.99	1.43	2.60E-01	0.01	3.17E-05	
Gen2 Dbl Pot	Gen2DPv3	3/3/2008	2.12E-03	0.97	0.86	4.36E-01	0.01	3.16E-06	0.78
Gen2 Dbl Pot	Gen2DPv4	3/7/2008	1.02E-03	0.99	0.09	5.22E-01	0.02	9.04E-05	0.53
Gen2 Dbl Pot	Gen2DPv4	3/21/2008	1.57E-03	0.99	0.81	3.73E-01	0.01	1.92E-05	0.53
Gen2 Dbl Pot w/Chimney	Gen2DPv5	4/7/2008	2.02E-03	0.99	1.16	2.60E-01	0.02	4.01E-05	0.66
Gen2 Dbl Pot w/Chimney	Gen2DPv5	4/7/2008	3.43E-03	0.98	1.30	3.38E-01	0.01	4.28E-05	0.48
S4100 Certification Test 1	1	10/22/2008	2.45E-03	0.99	1.57	1.71E-01	0.00	7.55E-05	0.30
S4100 Certification Test 2	1	10/22/2008							

Stove Model	½'s or #	Test Date	Methane/wood	Form	Form/Acet oc	Acet	gCeO/co2
Gen 2	Gen2 DP v7	1/11/2008	3.10E-03	0.11	0.00	0.10	3.34E-04
Gen 2	Gen2 SP v7	1/15/2008	2.07E-03	0.12	0.00	0.12	4.10E-04
Yue Xiang	YXv1	1/28/2008	1.83E-03	0.13	0.00	0.08	3.58E-04
Yue Xiang	YXv1	1/30/2008	3.83E-03	0.10	0.00	0.11	6.62E-04
Yue Xiang	YXv2	2/20/2008	4.07E-03	0.08	0.00	0.09	3.38E-04
Yue Xiang	YXv2	2/29/2008	2.64E-03	0.10	0.00	0.10	3.26E-04
Grey Hsil Ht	Hsil1	3/10/2008	1.97E-03	0.08	0.00	0.08	2.77E-04
Insulated RF		3/10/2008	1.91E-03	0.11	0.00	0.11	3.33E-04
Insulated I&L		3/11/2008	1.93E-03	0.08	0.00	0.07	2.96E-04
Uninsulated RF		3/21/2008	3.78E-03	0.11	0.00	0.10	1.93E-04
Water Jacket Ht		3/24/2008	2.06E-03	0.32	0.00	0.30	4.36E-04
Water Jacket RF		3/24/2008	2.08E-03			0.28	6.96E-04
S2100	1	4/7/2008	5.06E-03	0.10	0.00	0.10	4.15E-04
S2100	1	4/9/2008	1.46E-03	0.10	0.00	0.11	3.47E-04
S2100	1	5/20/2008	1.85E-03	0.11	0.00	0.11	3.58E-04
Gen2 Dbl Pot	Gen2DPv2	2/18/2008	3.13E-03	0.10	0.00	0.18	1.63E-04
Gen2 Dbl Pot	Gen2DPv2	2/12/2008	2.34E-03	0.10	0.00	0.10	2.31E-04
Gen2 Dbl Pot	Gen2DPv3	2/22/2008	4.83E-03	0.14	0.00	0.10	2.61E-04
Gen2 Dbl Pot	Gen2DPv3	2/26/2008				0.07	1.77E-04
Gen2 Dbl Pot	Gen2DPv3	3/5/2008	2.09E-03	0.07	0.00	0.08	2.20E-04
Gen2 Dbl Pot	Gen2DPv4	3/7/2008	1.00E-03	0.12	0.00	0.07	1.54E-04
Gen2 Dbl Pot	Gen2DPv4	3/21/2008	1.12E-03	0.10	0.00	0.07	1.56E-04
Gen2 Dbl Pot w/Chimney	Gen2DPv5	4/7/2008	1.40E-03	0.12	0.00	0.12	2.50E-04
Gen2 Dbl Pot w/Chimney	Gen2DPv5	4/7/2008	1.58E-03	0.09	0.00	0.13	4.70E-04
S4100 Certification Test 1	1	10/22/2008	6.45E-04	0.09		0.10	2.90E-04
S4100 Certification Test 2	1	10/22/2008					

Appendix B – Limit of Detection and Limit of Quantification

Cascade Impactor	
	-7.3
	3.3
	2.5
	-5
	10.5
	6.2
	4.3
	-2.5
	0.3
	-3.6
Standard Deviation	5.5
3*σ	16.6
10*σ	55.2

Gravametric Filter	
	2
	-3
	10
	1
	-4
	11
	4
	3
	6
	8
	7
	10
	6
	-5
	6
Standard Deviation	5.1
3*σ	15.3
10*σ	51.1

Appendix C – Nano-Moudi II Impactor Cutpoints

Stage	d_{50}, μm	Elevation Corrected d_{50}, μm
1	10.000	9.986
2	5.600	5.586
3	3.200	3.186
4	1.800	1.787
5	1.000	0.987
6	0.560	0.548
7	0.320	0.309
8	0.180	0.171
9	0.100	0.094
10	0.056	0.052
11	0.032	0.030
12	0.018	0.017
13	0.010	0.009

Source: Bennett, Maren. "Emissions from a Diesel Engine Operating with Soy-Based Biodiesel Fuel." Master's thesis, Colorado State University, 2007.