An Improved Wood Cookstove: Harnessing Fan Driven Forced Draft for Cleaner Combustion

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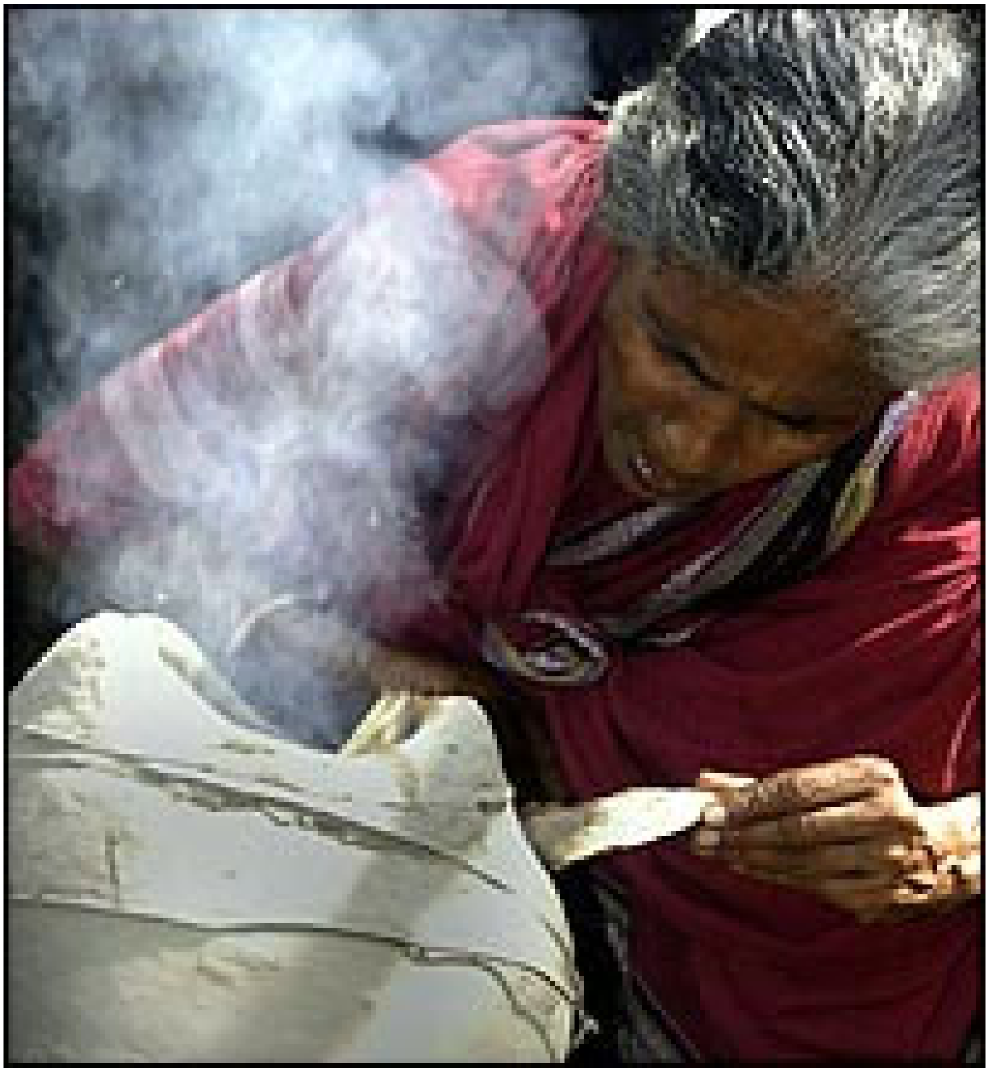

***A 'Traditional'chula in India.*[1]**

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Introduction

People around the world use wood and biomass as their primary fuel source. From China to Kenya, Guatemala to India, half of humanity cooks over woodfires. However, burning wood raises many issues about which to be concerned. Traditional wood burning stoves are terribly inefficient, unsustainable, and polluting. Thus, stove technology could be significantly improved upon to reduce these negative effects by increasing efficiency through advanced combustion techniques.

With respect to stove technology, the issues of efficiency and sustainability are inextricably linked. According to the NRDC, a governmental development agency in India, the traditional wood burning stove operates at around 6-10% thermal efficiency, as opposed to physically possible efficiencies that are many times greater. Furthermore, over 2 billion people worldwide are facing fuel shortages (Rouse). Forests in developing countries are rapidly decreasing and the ratio of forests-to-people is less than half of what it was in 1960. A 1989 study of 15 developing countries demonstrated a staggering demand for fuelwood. Of 669,000 hectares needed each year, only about 63,000 hectares are replanted - less than 10% of the demand. This trend of wood use is unsustainable and a widespread increase in stove efficiency could significantly reduce the resource stress and environmental impact. Furthermore, due to resource availability and the economic situation of the people who use woodburning stoves, the world’s poorer half, alternatives to wood and biomass energy are not currently viable or affordable. In fact, many families spend more money on fuelwood than on food, drastically affecting the nutrition levels of the family (Whitfield). Thus, by maximizing the efficiency of wood burning stoves both environmental, economic, and health gains could be achieved.

Wood burning stoves also create a great deal of pollution. Indoor air pollution has been ranked 8th in the health burden worldwide by the World Health Organization. The health burden relates to years lost of healthy life. In developing countries, which make up 40% of the world's population, it ranks 4th. The World Bank called indoor air pollution one of the four largest environmental problems facing the developing world today. Much of this pollution can be attributed to the use of wood burning stoves for cooking. The fine particulates and carbon monoxide released by wood from incomplete combustion cause acute respiratory ailments, ear and eye problems, breathlessness, chest pains, headaches, dizziness, and more – much of which affects women and children. Acute respiratory ailments are the biggest killer of children under five (Rouse). For some women cooking tortillas for sale in Central America, the inhaled particulate matter is equivalent to smoking 20 packs of cigarettes per day (Whitfield). This pollution also worsens local air quality in the community and contributes to global warming if the wood use causes deforestation.

Background

Previous Natural Draft Improved Stove Designs:

An extensive search of the literature has yielded many previous stove designs. The following is a smörgasbord of those designs.

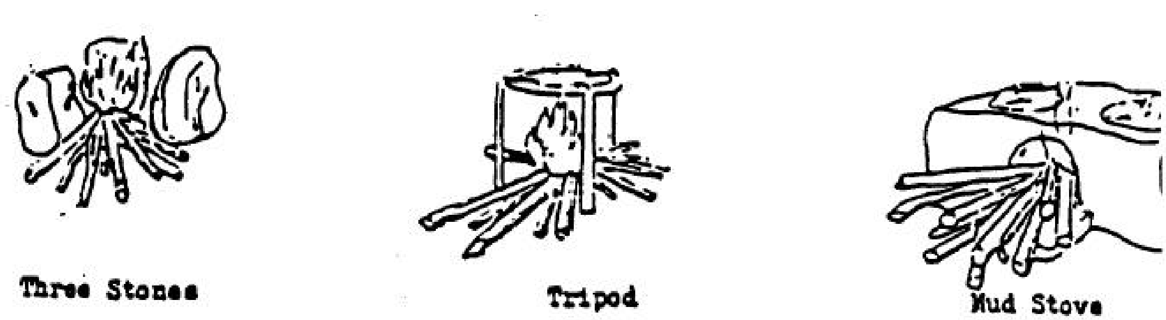

Figure 1: Pandey, Traditional Stoves.

Figure 1 shows three examples of traditional stoves in Nepal. These designs are basically open flames and do not incorporate any advanced principles of combustion. The three-stone fire will serve as a benchmark for quantifying the relative performance of this project's prototype. A further example of the traditional three-stone fire is in Figure 2. According to Baldwin, 82% of the energy lost in this system is lost to the ambient environment.

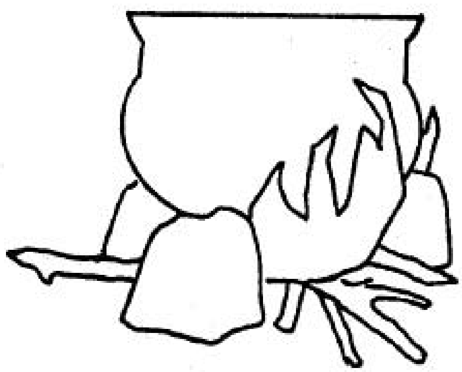

Figure 2: Baldwin, Traditional Open Fire.

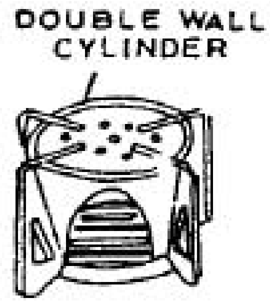

Figure 3: Rajpal, Design Concepts of Stoves.

Much improvement could be made by simply reducing that energy lost. For example, Figure 3 demonstrates a double wall cylindrical stove. This system would trap the heat inside the stove and direct it to the pot, thereby increasing thermal efficiency and combustion quality significantly.

Numerous other stove designs will improve upon the traditional stove design. Another example is the 'Rocket Stove' (Figure 4) designed by the Aprovecho Research Center. This stove uses a grate for the fuel bed to increase air flow and thereby increase combustion quality. The specifications of the stove height-to-volume ratio are such that an increased thermal efficiency is achieved and more of the energy produced actually reaches the stove.

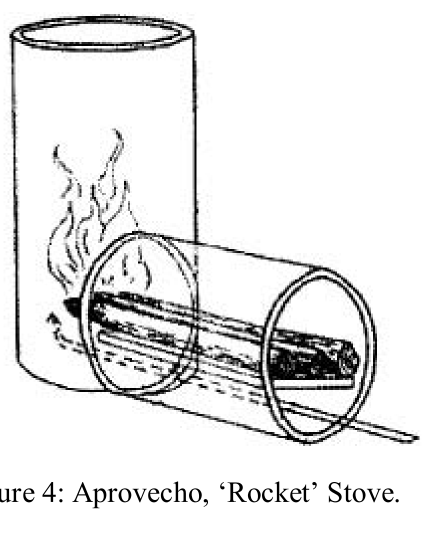

Figure 4: Aprovecho, 'Rocket' Stove.

However, this stove has its limitations. There is no insulation in the stove design and therefore the fire has more of tendency to smoke due to cooling near the walls and at the same time the direct contact of the flame with the walls allows heat to conduct out of the system decreasing the thermal efficiency. With these sorts of questions in mind, the new cookstove can be improved.

Previous Forced Draft Improved Stove Designs:

The concept of forcing air into a fire is not a new one. Historians assert that China first developed blast furnaces in the 5th century BC to make cast iron. Forcing air into a fire is an established and effective way to raise flame temperature and intensity and also to reduce emissions by encouraging complete combustion. Two previous fan-driven stove designs are discussed herein – the Gusto Woodflame (Figure 5) and the Tom Reed Woodgas (Figure 6).

Fig. 5: Gusto Wood Flame
Retail Price: 230.00 USD

Fig. 6: Tom Reed Woodgas
~~Retail Price: 99.00 USD~~

These stoves are used in average as a benchmark to measure relative success of this project's prototype. Each of them have their own limitations. For starters, both stoves are far too expensive to be considered for international development work. The Gusto has a retail price of 230.00 USD and is marketed to upper class North Americans as a bourgeois barbecue.

Nevertheless, it is a clean and effective stove. The Tom Reed Woodgas had a retail price of 99.00 USD before it was taken off the market for a defect – the fan burns out after about one hour of use. Thus, in order to reduce cost and increase accessibility, a new design for a fan-driven forced draft improved stove is necessary and will be pursued in this project. Fan burnout, cost, accessibility, materials used, and concept design will all be considered for the design.

Cultural Implications:

Finally, and perhaps the most important point, every community has its own customs, traditions, bias, relationships with innovations, level of social capital, and so on. For the stove to be useful, the design must take into account all of these factors. This will be the single most difficult part of this project. How does one design a stove for a community in which one has never been, does not know the people, does not know the intimate histories of the place? In the humble opinion of the author, one cannot, but for the purposes of this design project these factors will be integrated as best as is possible from thousands of miles away.

Methods

Project Plan:

The goal of this project is to design and fabricate a useful, inexpensive, efficient, non-polluting wood burning stove that is constructible and maintainable within the economic and technical limitations of communities in underdeveloped regions of the world. For genuine good to come out of such a project, the engineering must be culturally sensitive and relate to the history, needs, and lifestyle of those that would use the stove. Within the time, economic, and scale constraints of this project, success will, ideally, be determined by the level to which the stove meets the social needs and natural and economic resources of the target community. However, a beneficiary community could not be accessed from Trinity College in Hartford, CT with the budget and resources of a Senior Engineering Project. Thus, the main criteria for success depended on four ***Critical Criteria –*** Cost, Functionality, Emissions and Efficiency.

The four Critical Criteria lay out the necessary components of a successful stove project as a Senior Project. *Cost* relates to the economic burden each stove incurs. For all the target beneficiaries, money is not a luxury enjoyed. Thus, reduction in cost is imperative. Even if the stoves are subsidized through aid money, unit cost per stove must be a criterion for the project.

Functionality relates to the ease of use and operating reliability of the stove. The stove designed must be easy to use and must not break easily. The stove surface should have some defense against overheating for safety purposes. The life of the stove should also be accounted for. Lastly, and most importantly, the fan motor must not overheat as in the Tom Reed stove.

Emissions and *Efficiency* are related and are basically self-explanatory. For the stove to be useful it must reduce emissions of particulates and carbon monoxide, but it should also increase efficiency by lowering boiling time and fuel consumption.

The timeframe for this project is approximately 20 weeks with appropriate time allotted to the tasks of research in the necessary fields, theoretical analysis and design, fabrication, and testing of emissions and efficiency in the stove. Ultimately, the budget for design, fabrication, and testing of the apparatus will far exceed the final construction costs for one or many stoves. This is part of the economic objective of the project. See App. B for a complete project timeline.

Project Objectives:

The Emissions and Efficiency Critical Criteria for this project stem from an extensive search of the literature for both improved stoves and what is called 'traditional' stoves. See Table 1 below for the summary of engineering design goals.

Table 1: Engineering Performance Criteria / Design Specifications

	Literature		Project Objective
	Improved Avg.	~20%	

Thermal Efficiency	Traditional	~10%	>10%
SPM Levels (Suspended Particulate Matter)	Improved Avg. (at 5.5 kW)	3 mg/m^3	<5 mg/m^3 (at 5.5 kW)
	Traditional (at 5.5 kW)	5 mg/m^3	
Excess Air	Improved Avg.	24%	24%
Carbon Monoxide (±100 ppm)	Improved	0-4% (at worst, by burn rate)	<1%
	Traditional	2-3% (by post-ignition time)	
CO/CO_2 Ratio	Traditional	0.12	<0.12
Power Output	Traditional	0.7 kW	>0.7 kW (size appropriately)

The final stove design will be a compromise between the pull for performance in each of these areas. An example of the balance that must be considered is the relationship between thermal efficiency and combustion quality. One way to increase thermal efficiency, or the amount of heat produced that is absorbed into the pot to cook the food, is to bring the pot closer to the fuel bed. However, lowering the height of the stove reduces air flow and decreases combustion quality.

Power output and combustion efficiency are both unique parameters. Power output will be dependent on the level of power required to cook the food. Too much power output, or an inability to 'turn down' the stove power, will result in higher wood use than necessary and lower thermal efficiency. See below in the Preliminary Calculations section for more on power output. Combustion efficiency is notable because of its difficulty to quantify. Many of the losses in combustion efficiency come from particulates and unburned hydrocarbons lost out the flue or in unburned combustibles in the fuel bed. While these are hard to quantify, experimental determinations in the literature claim that these sort of losses account for less than 10% of the losses in stove efficiency. For these reasons, combustion efficiency in this sense will largely be ignored.

Furthermore, Quality Function Deployment (Table 2) was employed to clarify and quantify the user needs. The most important items to note are the customer requirements. For the stove to be effective, and by that the stove is actually considered useful by the target beneficiaries, it must meet customer requirements. See below for further explanations of the QFD parameters.

Table 2: Quality Function Deployment

Customer Requirements	Cost	Pollution Level - CO	Pollution Level – SPM	Thermal Efficiency	Combustion Efficiency	Power Output	Chamber Size	Chamber Shape	Use Clay	Use Metal	Useful Life	Safety Features	Space Occupied	Ergonomic Features	Labor Time for Construction	Remaining Char	CO/CO_2 Ratio	Excess Air
	Engineering Requirements																	
Cheap	x						x	x	x	x								
Easy to Build	x						x	x	x	x		x	x	x	x			
Easy to Use							x	x				x		x				
Easy to Maintain	x						x	x	x	x	x				x			
Materials Available	x						x	x	x	x	x			x	x			
Less Smoke		x	x	x	x	x	x	x									x	x
Less Wood				x	x	x	x	x								x	x	x
Effective				x	x	x										x	x	x
Units	$	%	mg/m^3	%	%	kW	cm^3	-	-	-	Years	-	cm^3	-	Hours	mg/%?	-	%
Engineering Targets	10	<1	<5	>10%	?	5.5 (med)	Portable?	TBD*	TBD	TBD	5(?)	TBD	Portable?	TBD	3(?)	?	0.12	24

*TDB ≡ To Be Determined

Under customer requirements, 'cheap' sits in the top row. With the inexpensive nature of the stove must come a perceived ease of trialability. Users must be comfortable with the notion of using the stove on a trial basis. They do not want to make great sacrifices for something that may or may not actually help them. With that comes the next category of customer requirements. Is the stove easy to use? Issues for comfort in cooking include the ease of ignition, the speed of cooking, the versatility of fuel supported, and the variety of pot size, shape, and type supported. The great advantage of traditional stoves, that must be met or exceeded by improved stoves, is their great versatility, both in fuel and pot type supported and ease of use. Finally, the improved stove must be effective in cooking the food. If the improved stoves are perceived as taking too long to cook or not cooking food properly, they will not be used.

Other cultural factors cannot be ignored and must be studied in detail. For example, do the women traditionally mop the floor after cooking and will the hot ceramic stove crack if the wet mop contacts it? Do the people traditionally cook a large millet soup in a big bowl that requires a lot of stirring and stress on the stove? Do the ground vegetables they eat require extensive cooking to be edible? These factors must be taken into account if the level of use for the stove will ever exceed the dismal rates occurring in India and Nepal at as low as or lower than 20% (Pandey).

Project Breakdown

Preliminary Design Calculations:

Preliminary calculations were performed to determine the needs of power output required. The energy required to bring one gallon of water from room temperature (20˚C) to boiling (100˚C) was calculated for various time frames (see Appendix A for complete calculation).

30 mins (1800s) → **0.705** kW
20 mins (1200s) → **1.058** kW
10 mins (600s) → **2.115** kW

Now, the energy lost during boiling is needed to determine the total energy required to bring to boil and to maintain boil. For a covered pot of 28 cm diameter and 10 cm exposed to ambient air, the energy lost = 104.7 W = **0.1047** kW (Appendix A). This is at the highest rate of energy loss. In reality, the energy lost during the process of boiling will be less and increase as temperature increases. This value of energy lost is the total required to maintain boiling. To determine the energy required to reach boiling simply add the values above to the value for energy lost. In Kandpal (1995), a study of particulate matter pollution in cookstoves, the median energy output was about 5.5 kW. But other sources (Rajpal) match more closely the approximate 0.7 kW output of a traditional stove. An explanation for this anomaly has yet to be determined but may stem from other significant energy losses in the above mentioned 5.5 kW stove.

Preliminary Design Concept Testing:

In order to design the stove components, data for stoichiometric air flow and pressure drop were needed. For this a fan testing apparatus was designed and built to test pressure drop of various fans. The basic premise is that of a scaled-down wind tunnel. A pitot-static tube and an inclined red oil manometer were used to measure pressure created by each fan. See Figure 7 below.

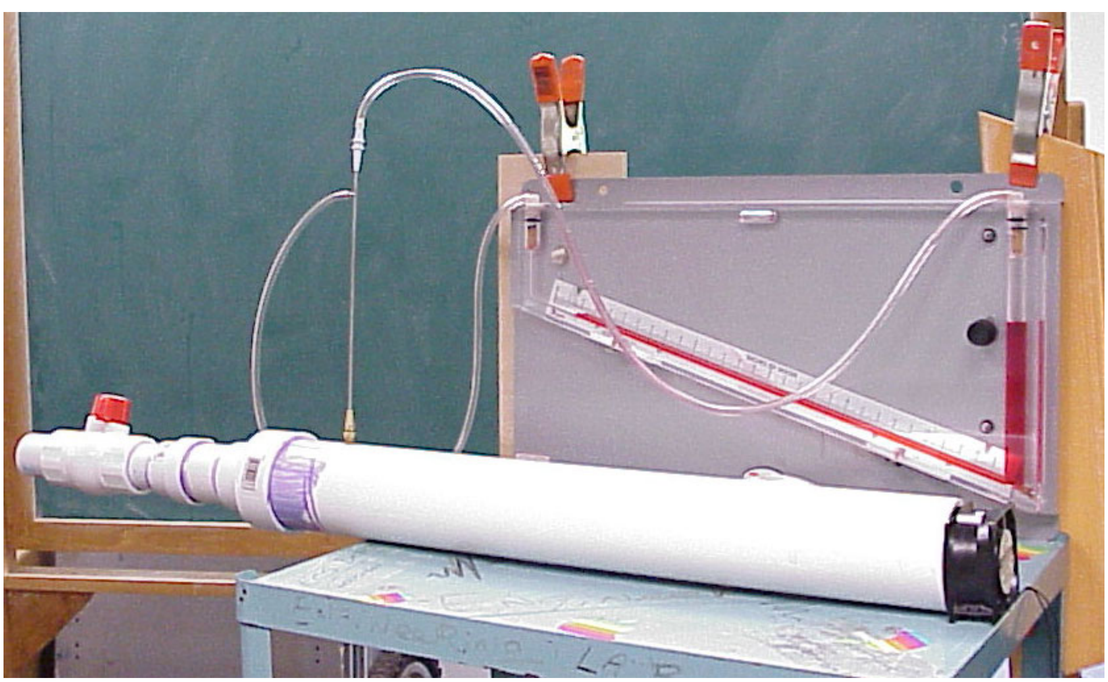

Fig. 7: Photo of wind tunnel setup for testing fan pressure drop.

Data was obtained by incrementally by closing a globe valve and recording pressure. A centrifugal fan and a computer-cooling fan were both tested. From this data, a chart of Volumetric Flow vs. Pressure Drop was created and used during design for the stoichiometric air flow. See Figure 8 below to see the chart generated for the centrifugal fan. The computer cooling fan created a total pressure of 0.20 in H_20. On the other hand, the centrifugal fan tested created a total pressure drop of 2.33 in H_20. The cooling fan is a simple blower fan and therefore cannot sustain a significant pressure drop. When a certain pressure in a tunnel is reached, blowback occurs. This is particularly bad when dealing with the hot air of a fire and could contribute to fan motor burnout. Thus, the centrifugal fan was chosen. The higher pressure drop both increases flow through air jets and prevents blowback and fan motor burnout.

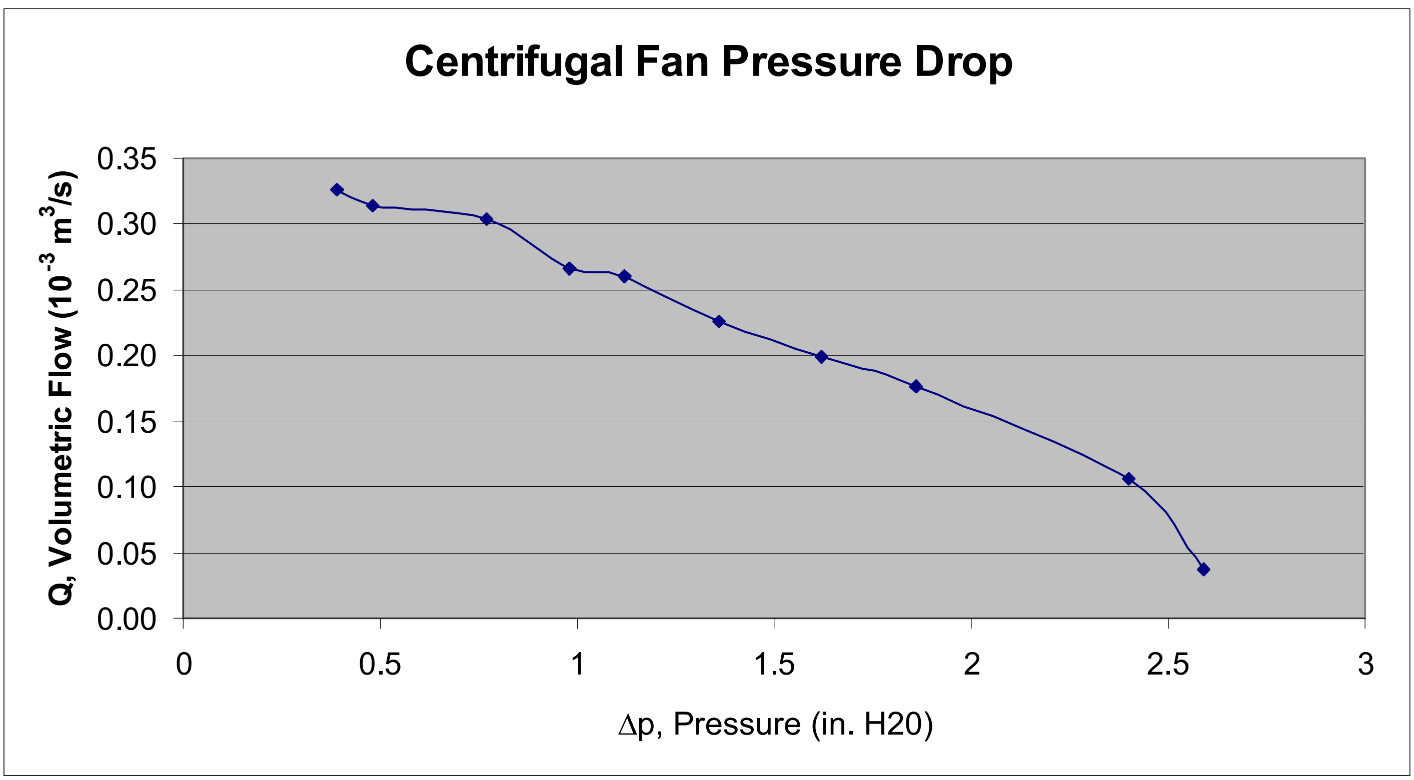

Fig. 8: Plot of Volumetric Air Flow v. Pressure Drop for Centrifugal Fan Used in Prototype.

Prototype Design:

A prototype was designed based on initial concepts of combustion. The main obstacle to reaching complete wood combustion is the difficulty in creating good mixing between the fuel and air. When wood combusts, volatiles are released from the wood as gas and then the gas ignites when mixed with air and spark. Using this principle, a two-stage combustion system was designed and implemented using the forced air convection from a centrifugal fan. Incomplete combustion occurs in the lower, fuel-rich region using small vertical air jets. In the higher, fuel-lean combustion region, the gas fuel and air are further mixed using larger horizontal air jets. This allows for a much hotter and cleaner combustion process. See Figure 9 below for a rough design schematic.

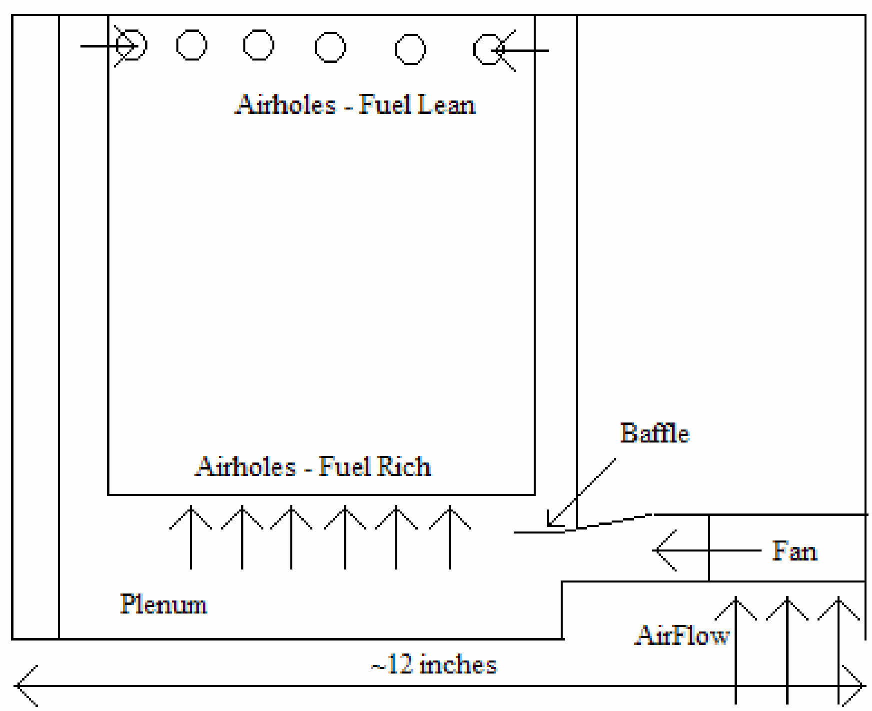

Fig. 9: Design Schematic of Stove Prototype.

Following flow along with Figure 9, the centrifugal fan brings in air and forces it through a duct into the plenum. The plenum, then, is a pressure area and a pressure drop exists across both the lower and upper air holes. This pressure drop drives air flow into the combustion chamber.

Design Calculations:

In order to design for the size and quantity of air flow holes in the alpha prototype, some simple calculations were performed. An overview of those calculations is presented below in the flowchart of Figure 10. The following several sections are devoted to a more thorough explanation of each calculation performed to reach the prototype design.

Fig. x: Design Calculations Flow Chart

Fig. 10: Flowchart of Design Calculations.

Required Stoichiometric Air Flow

↓

Limiting Characteristic Time for Volatization

↓

Equivalence Ratios in Combustion Chamber

↓

Jet Penetration for Air Flow

↓

Prototype.

Calculation of Air Flow Required:

The initiating concept upon which all of the following calculations depend is the chemistry of wood combustion and creating stoichiometric conditions for combustion. A balanced equation for the combustion of wood follows:

$$C_{50}H_{72}O_{33} + 26.5(O_2 + 3.76N_2) \rightarrow 25CO_2 + 36H_2 0 + 99.69N_2$$

The change in enthalpy, ΔH_{rxn}, can be determined from enthalpies of formation (Table 3 below) for each species and from the following formula: $\Delta H_{rxn} = \Delta H_{reactants} - \Delta H_{products} = Q$.

Table 3: Enthalpy of formation for species in wood combustion.

Species	Standard Enthalpy of Formation
Wood (C50H72O33)	Assume = 0
Oxygen (O2)	0
Nitrogen (N2)	0
Carbon Dioxide (CO2)	-94,054 kcal/mol
Water (H20)	-57,798 kcal/mol

This gives an enthalpy of reaction of 4573.16 kcal/mol. Knowing ΔH_{rxn}, we can use Equation 1 and our preliminary calculation of Power Needed (0.705 kW) to obtain the Air Flow Required in cubic meters per second to be **$1.113*10^{-4}$ m^3/s**.

$$\frac{\Delta H_{rxn}}{t} \times \frac{molesAir}{\Delta H_{rxn.air}} \times \frac{m^3}{mole} = \frac{m^3}{s} \qquad \text{Equation 1.}$$

Furthermore, values for associated fuel required can be obtained from similar simple molar manipulation.

Calculation of Limiting Characteristic Time for Volatization:

First, the rate of volatization was needed to determine required stoichiometric air flow. Pyrolysis and heat transfer through the wood both play a role in volatilization. Thus, characteristic times for both were determined using the equations below.

Pyrolysis:

Pyrolysis was determined using both Equations 2 and 3. Equation 2 was calculated for a flame temperature of 800C. Equation 3 was integrated to obtain the characteristic time, τ_{char}.

$$k,_{pyr} = k_{o,pyr} \exp\left(\frac{-E_{pyr}}{RT_p}\right) \qquad \text{Equation 2.}$$

$$\frac{dmv}{dt} = -m_v k_{pyr} \qquad \text{Equation 3.}$$

Heat Transfer:

In order to determine the characteristic time for volatization due to heat transfer, the wood fuel was modeled as a frictionless sphere of mass = 100g. Two primary equations were used in this calculation (Equations 4 & 5) and then set equal to one another to determine characteristic time.

$$\dot{Q} = mC_p \frac{dT_w}{dt} \qquad \text{Equation 4.} \qquad \dot{Q} = \bar{h}\Delta TA = \bar{h}(T_{fire} - T_{wood})A \qquad \text{Equation 5.}$$

Thus, characteristic time can be obtained from Equation 6. A rough value for enthalpy, h, was obtained using the Reynolds number and Figure 6-12(pg. 293) of JP Holman, “Heat Transfer.”

$$\Delta t = \frac{mC_p \Delta T_w}{\bar{h}(T_f - T_w)4\pi R^2} \qquad \text{Equation 6.}$$

From Table 4 below, heat transfer is shown to be the limiting characteristic time for volatization.

Table 4: Limiting Characteristic Time for Volatization

Method of Volatization	Characteristic Time, τ_{char}
Pyrolysis	0.136 s
Heat Transfer	**20.3 min**

Thus, a 100 g piece of wood at 800 C will take approximately 20.3 min to completely volatize. This is a very rough value because of the many assumptions made in obtaining it and furthermore, in actual flame conditions radiation from neighboring fuel will increase volatization rate. This is enough to work from, however.

Calculation of Equivalence Ratios in Combustion Chamber:

In order to obtain the proper mixing of fuel and air, equivalence ratios were required for each of the flow areas – the lower fuel-rich zone and the upper fuel-lean zone. A calculation of equivalence ratio at the designated adiabatic flame temperature of 800C based on inlet temperature/pressure and fuel used is appropriate here. However, these sort of combustion calculations can be very tedious and require extensive iteration. Thankfully, computer programs have been developed to do this for us. Using Chris Morley's Gaseq Chemical Equilibrium program, with inlet temperature of 300K and pressure of 1 atm, and with wood approximated as iso-octane (C_8H_{18}), an equivalence ratio of Φ=3.0 is obtained. This implies that one third of the airflow should go to the lower fuel-rich zone and two-thirds should

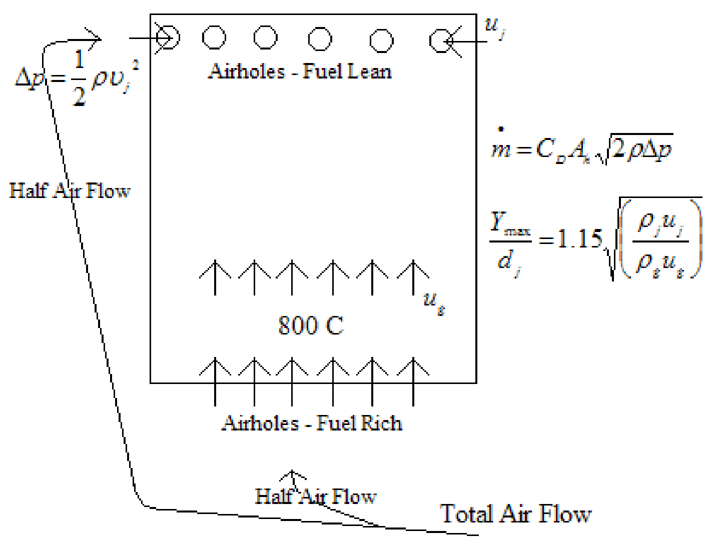

Fig. 11: Detail of Combustion Chamber Schematic of Stove Prototype.

go to the upper fuel-lean zone. However, significant losses from heat transfer to the environment and moisture content in wood cause the need to reduce this ratio to a rough guess of about Φ=2.0. This implies that total air flow should be divided in half between upper and lower combustion stages, as in Figure 11 above and like so: $\dot{A}ir_{lean} = \dot{A}ir_{rich} = 0.5\dot{A}ir_{total}$.

Calculation of Jet Penetration for Air Flow:

The final calculation step before prototype fabrication was to determine hole sizes and jet penetration. For the fuel-rich initial combustion stage, *distribution* of air flow was desired, so smaller holes were used. For the fuel-lean mixing stage, *penetration* was desired, so bigger holes were used. The sizes were chosen from an iteration process using the equations below: Equation 7 for the mass flow rate of air at a certain pressure drop and Equation 8 for the jet penetration.

$$\dot{m} = C_D A_h \sqrt{2\rho\Delta p} \qquad \text{Equation 7}$$

$$\frac{Y_{\max}}{d_j} = 1.15\sqrt{\left(\frac{\rho_j u_j}{\rho_g u_g}\right)} \qquad \text{Equation 8}$$

Notice the term for pressure drop in Equation 7. This was determined using the required air flow found above of $0.113*10^{-4}$ m^3/s. This value was correlated on Figure 8 for the volumetric flow versus pressure drop to obtain the needed pressure drop for the prototype. This pressure drop was then used to determine jet penetration. See?! All these calculations do eventually come together!

In Fig 11 above, notice that jet penetration is most important in the fuel-lean region. For Y_{max}, jet penetration, of half the combustion chamber diameter of 13 cm, jet diameter should be about 1.5 mm. Deeper jet penetrations arise from larger diameters, but losses will occur. Thus, the diameter for the upper fuel-lean holes was chosen to be 2 mm.

Now that jet diameter for one zone has been chosen, the remaining pieces fall into place. Even spacing of ¾ in. for the fuel-lean holes at a circumference of 15.7 in yields 20 holes. From the total air flow needed of $1.113*10^{-4}$ m^3/s and knowing that the flow should be divided in half, size and quantity of both upper and lower air flow holes can be determined. Table 4 below shows these specifications.

Table 4: Air Flow Jet Specifications for Prototype.

Combustion Zone	Air Flow Hole Jet Diameter	Number of Air Holes
Fuel-Rich (lower)	1 mm	40
Fuel-Lean (upper)	2 mm	20

Prototype Fabrication:

The frame for the prototype was fabricated using 22-gage (??) steel sheet metal. The combustion chamber and plenum sleeve were fabricated using chimney pipe. The scroll was machined from a 1.5 in x 3 in x 3 in section of solid aluminum stock. The duct was fabricated using sheet metal and sealed using blue poster ticky-tak. During initial testing for air flow, significant losses prevented any tangible sensation of air flow. The losses were mostly due to improper sealing between the sheet metal components. To rectify the problem, Cotronics furnace putty was used along all joints between components that involved air flow. A tap was drilled into the duct to measure pressure drop. With the added sealing, flow became physically apparent and pressure drop increased to between 0.82 to 1.14 in H_20 – right around the design specification of 1 in H_20. The prototype was ready for initial burn testing. Power was supplied to the DC fan using a DC power supply. Dialing down the voltage resulted in a reduced fan speed. In this way, fan speed can be controlled and therefore, burn rate can be regulated. See Figures 12 and 14 on the following page for photographs of the first iteration of the stove alpha prototype.

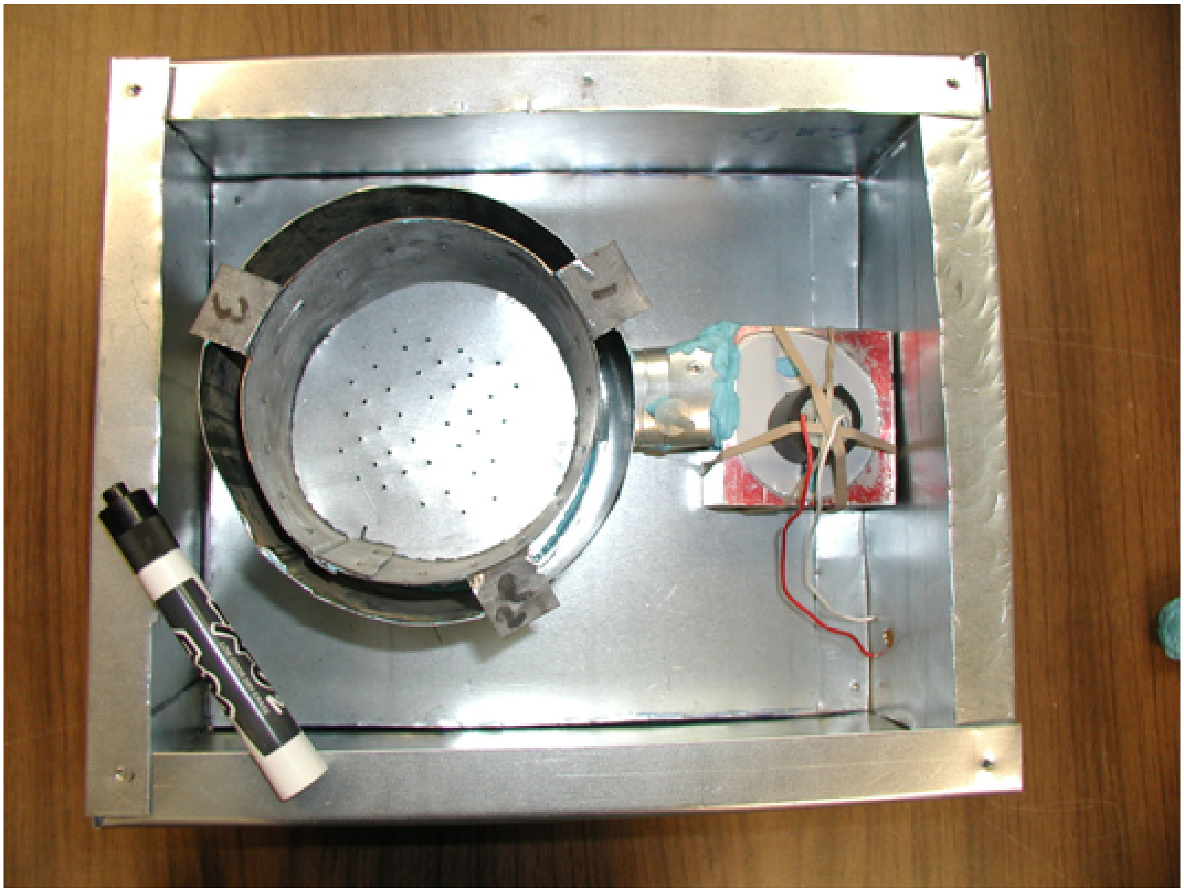

Fig. 12: Top View of Alpha Prototype.

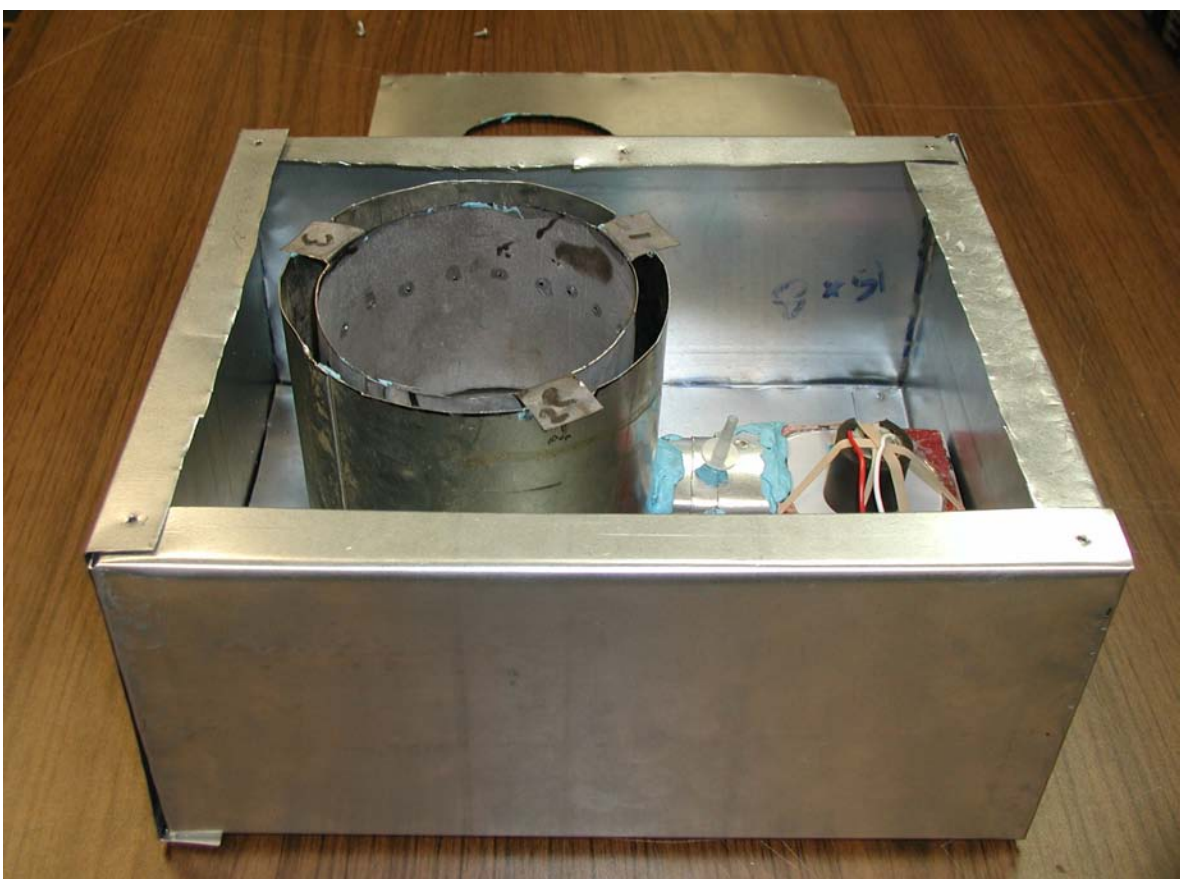

Fig. 14: Angled Top View of Alpha Prototype.

After an initial burn test, it was clear that a good, hot fire was created. Concerns raised included the ease at which the brittle furnace putty cracked and the significant increase in fan scroll and fan motor temperature. The most pressing concern was the fan motor temperature as fan motor burnout violates the Functionality Critical Criteria. The first design iteration, a radiation shield of aluminum foil added between the combustion chamber area and the fan area, did not significantly affect this temperature increase. The next design iteration was more drastic. It was thought (and hoped) that the temperature increase was occurring primarily due to heat transfer conduction through the metal components of the stove and NOT through air flow blowback in the fan. If blowback was occurring, big problems in the design of the stove would need to be addressed. To rectify the problem, ½ in diameter holes were drilled on all four sides of the stove body. These were to have the dual purpose of preventing conductive heat transfer and encouraging convective cooling within the stove body. Fortunately, it worked! The fan motor remained cool throughout the next 45 min burn trial and through the complete efficiency and emissions testing – a rigorous three-hour ordeal performed at Aprovecho Research Center.

Additional prototype modifications included the mounting of a 25Ω potentiometer on the stove body to regulate fan speed and the rigging of a simple head splitter plug from the fan motor leads. This splitter conveniently plugs into an AC/DC adapter so that the stove can be plugged into any standard 120 VAC outlet. This eliminated the need for the DC power supply and for batteries – which were considered but opted against due to short charge life (9V ran out too quickly, D-cell could have been tried). Also, pot supports were added to allow airflow into the combustion chamber and heat transfer to the pot.

The prototype stove is currently located at Aprovecho Research Center. Unfortunately, photographs were not taken of the stove prototype just prior to shipment for testing. Figures 12 and 14 were taken of the first-cut prototype. Thus, the added stove body air holes, the mounted potentiometer, the radiation shield, the sealing putty, and the pot supports are not shown.

Prototype Testing:

Testing for the stove was performed at Aprovecho Research Center in Cottage Grove, Oregon. A complete Water Boiling Test was conducted under an exhaust hood and contains three parts – cold start, hot start, and simmer. Figure 15 at right shows the testing setup at Aprovecho. During the test, all of the exhaust from the stove was collected by the hood and analyzed using a Nephalometer for particulates and an Enerac Gas Chromatograph for CO. Rough values for flame temperature were also obtained using thermocouple probes. Mass, moisture content, and species of wood were recorded. Through this test, data for the emissions output and fuel efficiency were obtained. The results are displayed below. (See Appendix C to see the Test Plan for the author's initial Aprovecho stove apprenticeship in January 2005.)

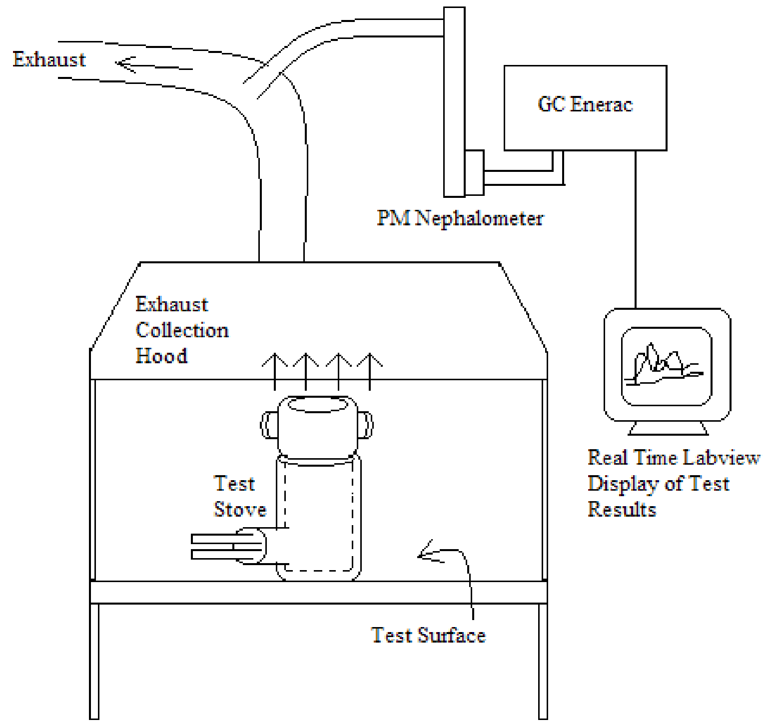

Fig. 15: Aprovecho Emissions Test Setup.

Results

The following four charts were obtained by Aprovecho Research Center using the testing setup developed there – an improvement on the basic Water Boiling Test. Tami Bond at University of Illinois at Champaign-Urbana conducted the subsequent data reduction, the details of which remain a mystery to the author. These charts relate to two of the Critical Criteria – Emissions and Efficiency.

The same setup follows for each chart. For all four, values for comparison are the three-stone open fire (blue) and an average of two similar fan stoves – the Gusto and the Tom Reed – (purple), with beige being the results for the Witt Alpha Prototype.

Emissions Results

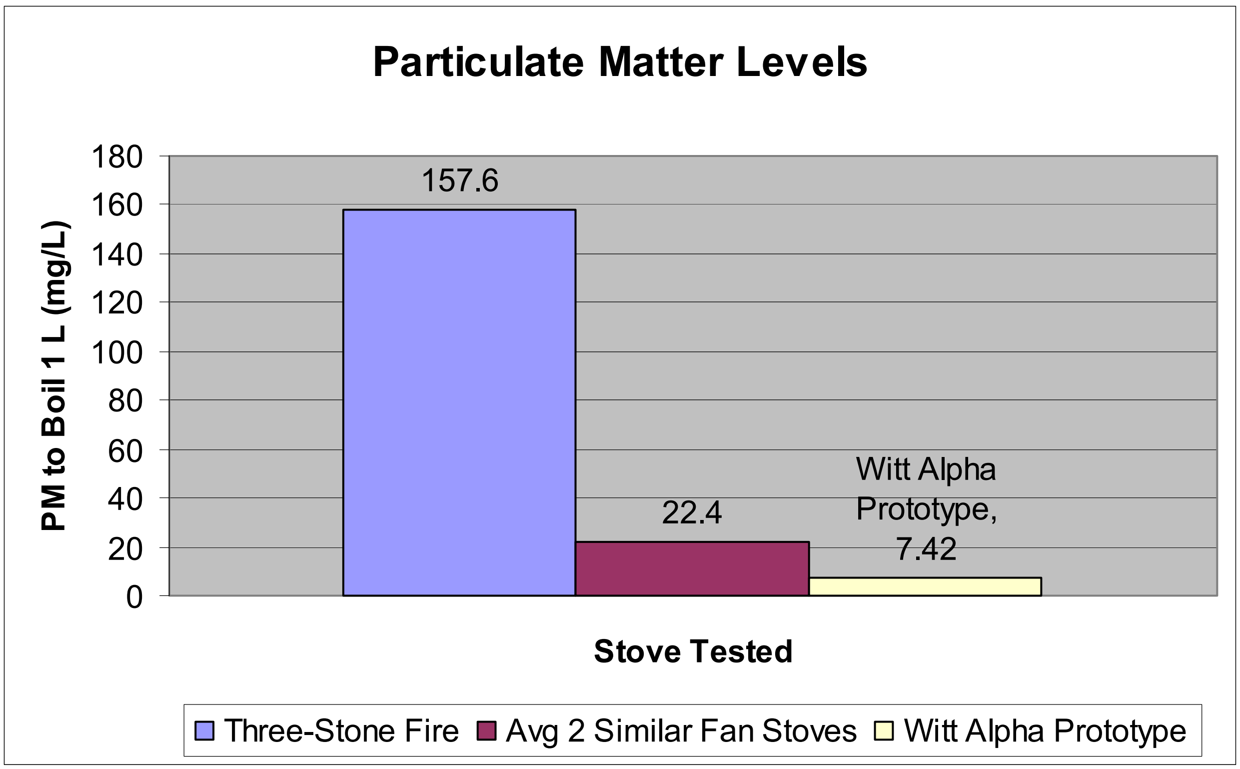

Fig. 16: Particulate Matter Levels.

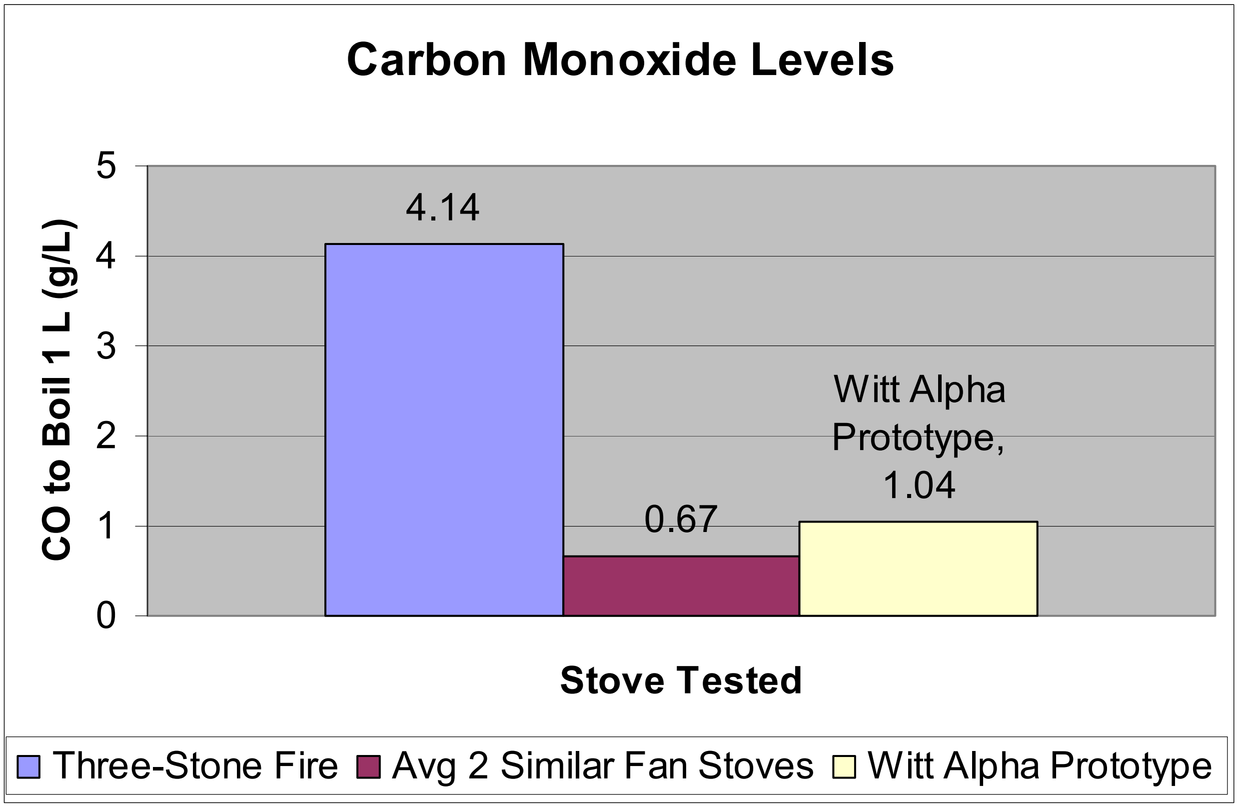

Fig. 17: Carbon Monoxide Levels.

Efficiency Results

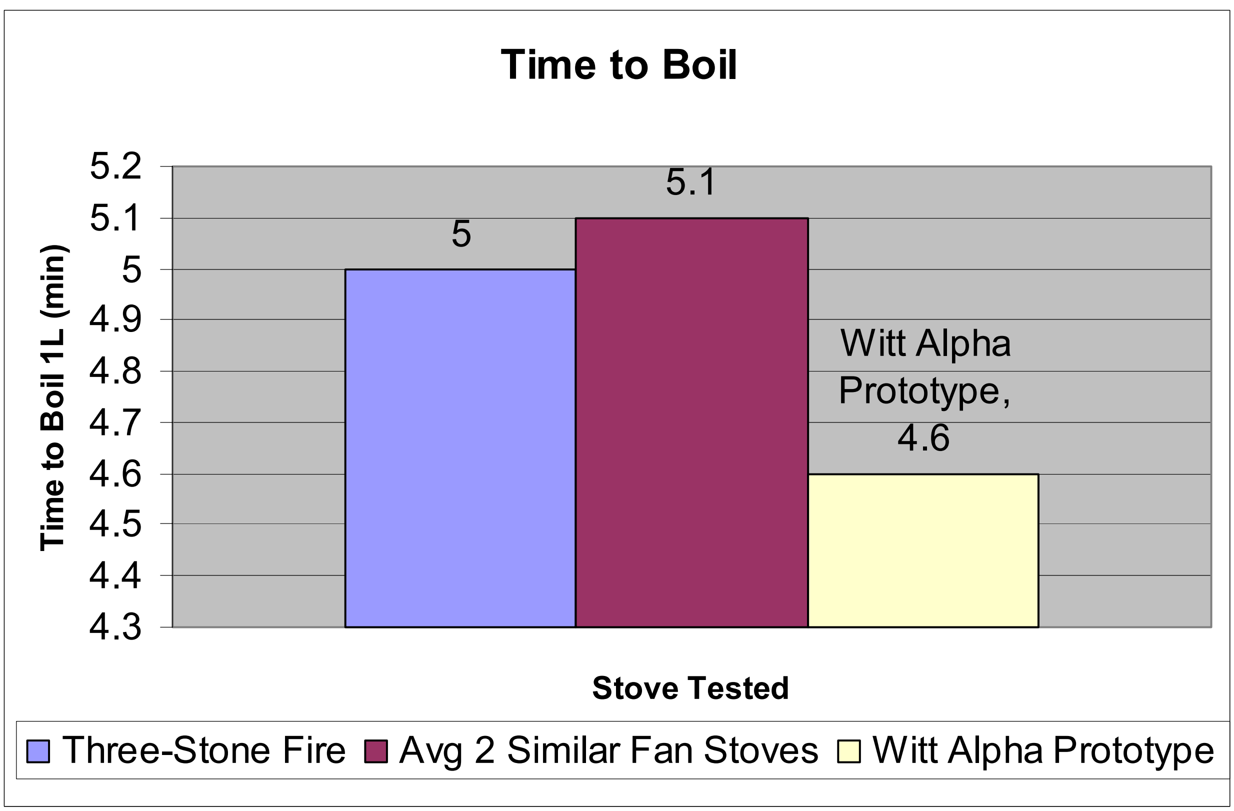

Fig. 18: Time to Boil 1 L Water.

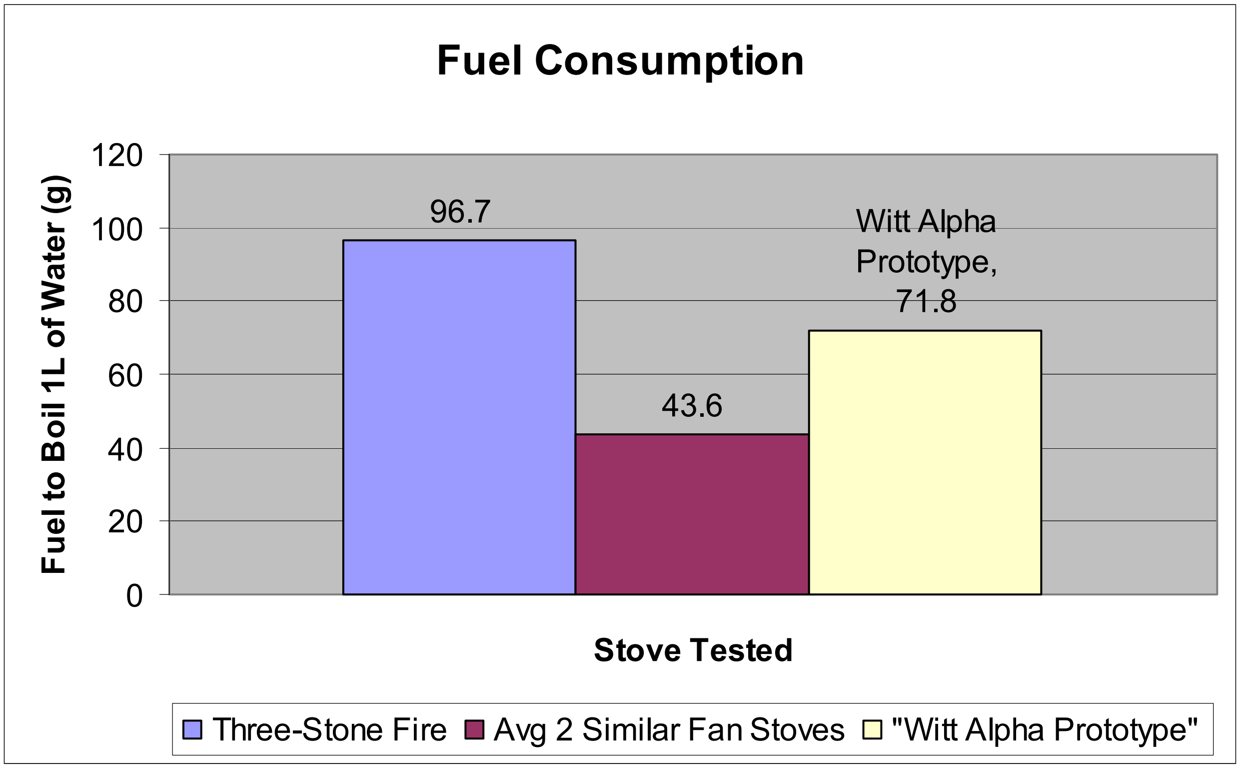

Fig. 19: Fuel Consumption to Boil 1 L Water.

Discussion

As mentioned above, four Critical Criteria were established for this project – Cost, Functionality, Efficiency, and Emissions. These will be discussed in reverse order.

Emissions Criterion:

Figures 16 and 17 demonstrate and compare emissions release between three stove categories – three-stone fire, similar fan stoves, and the Witt Alpha Prototype. Before delving into detail, it is worth noting that these levels for the three-stone fire are low. They were performed under laboratory conditions by technicians familiar with ideal fire-making methods. The wood fuel was metered carefully so that only tips burned and the sticks were placed so that natural convection could bring in the maximum amount of entrained air. This means that the emissions values for the three-stone open fire are especially low, whereas in the field the same stove produces several times more pollutants. This can be said of the other stoves tested as well, but none of them are as susceptible to variation in user skill level.

Particulate Matter Levels: Emissions of particulates is of significant concern due to the high correlation between PM levels and respiratory illness. Figure 16 shows that the particulates for the Witt Alpha Prototype were reduced by 96% as compared to a three-stone fire and by 67% as compared to the average of two similar fan stoves. This is really good.

Carbon Monoxide Levels: Figure 17 shows that in the Witt Alpha Prototype, CO levels were reduced by 75% as compared to the three-stone fire. Unfortunately, CO levels were slightly higher than in the two similar fan stoves, but remain comparable. The reasons for this are unknown. Designing a better system for preheating the flow of air could help to reduce CO emissions.

Efficiency Criterion:

Fuel Consumption: Reduction of wood consumption could create positive benefits in reduced economic impact for wood buyers and reduced collection time for wood gatherers. Figure 18 shows that the consumption of wood to boil 1 Liter of water for the Witt Alpha Prototype was in the midrange between the three-stone fire and the similar fan stoves. Not bad, but there is room for improvement. This may have something to do with the high firepower of the stove. Notice that time to boil is reduced. There may be a design trade-off between fuel consumption and boil time. One possible way to reduce fuel would be to lower the fan speed so that the wood burns more slowly. On the other hand, this brings in another design trade-off – reducing fan speed and thereby air flow could increase emissions.

Time to Boil: Reduction of boil time could create positive benefits in a reduced cooking time, allowing women and others who cook more time for other activity. Figure 19 shows that the Witt Alpha Prototype reduces boil time from 8-10% with respect to the three-stone fire and similar fan stoves. As mentioned above, this reduction in boil time and increase in firepower could be responsible for the increase in fuel consumption with respect to the similar fan stoves.

Nevertheless, for this design prototype, Efficiency was at the bottom of the priority list. Emissions goals were met with resounding success because of the design characteristics in bringing fuel to complete combustion. Completing combustion has very little affect on stove efficiency. The limiting factor for efficiency is heat transfer from the fire into the pot. The most effective ways to increase efficiency are methods that incorporate heat transfer principles in getting the energy created in the fire into the pot by forcing the hot flue gases to contact the pot longer. These include skirts, inset pot holders, beveled flue gas runs, and proper pot support gap.

Functionality Criterion:

The functionality criterion would best be evaluated using a field survey but the time and resources for such an undertaking were not afforded here. In short shrift, though, the stove is relatively easy to use. One item of concern is the necessity for batch loading, meaning that the user will have to remove the pot and refill the wood about every ten minutes. The main success of the stove was the longevity of fan life. After three hours of testing at Aprovecho the fan motor did not burn out, implying that a critical temperature increase will not be reached in this stove design.

Cost Criterion:

The cost for the alpha prototype far exceeded the design goal of approximate 10.00 USD. This was in large part due to Shipping&Handling and Testing Fees. A rough estimate of future cost is between 10.00-20.00 USD. The AC/DC Adapter is expensive and if possible, should be designed away from by utilizing an AC fan motor. The sheet metal and furnace putty costs can virtually be eliminated if the stove is made of mud or clay. That would leave chimney pipe and fan motor as the primary price tag components. See below in Table 5 for the project budget breakdown.

Table 5: Project Budget Expenditures:

Date	Purpose/Item	Vendor	Unit Price	Quantity	Subtotal
3/11/2005	Steel Sheet Metal	Loews	$ 25.95	2	$ 51.90
3/19/2005	Hi-Temp Ceramic Putty	Cotronics	$ 17.95	1	$ 17.95
4/11/2005	AC-DC Adapter Prototype	Cables&Connectors	$ 21.99	1	$ 21.99
4/12/2005	Shipping&Handling	UPS Store	$ 64.00	1	$ 64.00
5/1/2005	Aprovecho Testing Fees	Aprovecho	$ 100.00	1	$ 100.00
				TOTAL:	$255.84

Conclusions

As with any Alpha Prototype, during the fabrication and testing phases issues arose that will require design iteration:

* Maintaining seal – the use of ceramic furnace duct putty to seal the combustion chamber and plenum caused problems. The putty was very brittle and would break off, losing the pressure seal. This could be solved using mud or clay for the stove body, creating a better seal and potentially reducing unit cost of stoves as well.

* Pot supports – pot support height above the combustion chamber was chosen randomly. Future analysis should include effects of different pot support heights and implement in stove design.

* Unit cost – the unit price for fabrication of the prototype far exceeded projected goals. This can, of course, be reduced dramatically in future designs. Nevertheless, concerns still exist on the cost of the materials for the combustion chamber, duct, and scroll, for the fan/motor, and for the power supply.

* * *

Indoor air pollution from biomass stoves in developing countries contributes to health burden and economic strain. Traditional wood burning stoves can be improved upon significantly and inexpensively by using advanced combustion technology. The technical solution laid out herein is the design and dissemination of an improved cooking stove that employs fan-driven forced draft to clean up combustion and is only one effective means by which to improve stoves and reduce pollution, thus contributing to the ‘toolbox’ of available design solutions in the field. However, cultural factors that contribute to stove use must be taken into account when designing any improved stove. Only then can an improved stove project truly benefit the quality of life in underdeveloped communities. While this project has constraints of time, resource, and remote relation to the target beneficiaries, much societal good and personal growth can be realized implicitly from the work towards understanding the relationship between a small cultural community and the role of the engineer.

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Cover Photo

1: Bhattasali, Amitabha. A silent killer of rural women. BBC News, Calcutta. 2 March 2005.

Acknowledgements

I would like to thank the Trinity College Engineering Department for their efforts to mold me into a truly civically-minded engineer of the future. Their help, expertise, and support were invaluable for my education and this project. I would also like to acknowledge the contributions of those great people at Aprovecho Research Center – Dean Still, Nordica, and Damon Ogle – without their support, guidance, and contributions this project would not have been a success. Dr. Tami Bond at University of Illinois at Urbana-Champaign completed the data reduction for the test results. Thanks to Dr. Suzana Popovic for helping to start the process of a computer aided finite element analysis of fluid flow, even though that portion of the project was never completed. Many thanks to the funding support from Dr. Joseph Palladino, Engineering Department Chairman, Dr. Alison Draper, Trinity College Science Center, and the Student Government Association for my two-week trip to Aprovecho for a stove apprenticeship. Finally, I would like to thank the Chrisses. A thousand thanks to Chris Wynschenk, Engineering Lab Technician, for his incredible support both with technical expertise and creative ideas. And to Chris Orde, who tirelessly contributes to the Trinity Engineering community with her unflinching cheer and genuine pride for student work (and she lent me stove books from her husband!). The Traveler's Foundation contributed funding for the project.

Appendix

A:
Energy required to bring one gallon of water from room temperature (20˚C) to boiling (100˚C):
$\Delta E = \Delta h = h_2 - h_1$ where State 2 is boiling H_2O and State 1 is room temperature H_2O.

$$h = u(T) + pv$$

@5000 kPa, 20˚C: u=83.64 kJ/kg, v=0.00100 m^3/kg
@101.3 kPa, h_1 = u+pv = 83.64+101.3*0.00100 = 83.74 kJ/kg

@101.3 kPa, 100˚C, $h_2 = h_f$ = 419.02 kJ/kg

$\Delta h = h_2 - h_1$ = 419.02 - 83.74 = **335.28** kJ/kg

$mass_{H2O}$ = 3.785*10^{-3} m^3 *0.00100^{-1} kg/m^3 = 3.785 kg

ΔE = 335.28 kJ/kg * 3.785 kg = **1269.03** kJ

To bring to boil in:

30 mins (1800s) → **0.705** kW
20 mins (1200s) → **1.058** kW
10 mins (600s) → **2.115** kW

Now, the energy lost during boiling is needed to determine the total energy required to bring to boil and to maintain boil. For a covered pot of 28 cm diameter and 10 cm exposed to ambient air,

Surface Area Exposed of Pot = 0.14954 m^2
Heat loss rate = 700 W/m^2 (Baldwin, pg. 262)
Thus, the energy lost = 104.7 W = **0.1047** kW

B:

Project Plan:

Table B1: Projected Plan

Progression	**Task**
Mid-November/December	Literature Search/Theoretical Analysis/Engineering specification goals
January 7-21 (Winter Break)	Stove Apprenticeship, Aprovecho, Eugene, OR, Preliminary Testing
February	Design Alternatives. Design Constraints, Calculations. Fan Testing. Computer modeling?
March	Fabrication of prototype.
Spring Break	Send Prototype to Aprovecho for Testing.

April	Testing and Refinement. Iterate design of Motor/Fan Configuration. Computer Modeling?
April-May	Presentations and Reports

C:

Aprovecho Trip TEST PLAN*

* Baldwin, Primary Source for all material unless otherwise noted.

Performance Criteria:

Percent Heat Utilized (Thermal Efficiency) – percent heat released by fire that is absorbed by pot.

$$PHU = \frac{4.186W_i(T_f - T_i) + 2260(W_i - W_f)}{M_w C_w - M_c C_c}$$

(pg. 84, Baldwin; verified by Article (3), pg. 397)

Specific Consumption (SC) – <u>Total Quantity of Wood Used</u>
Amount of Water "Cooked"

$$SC = \frac{M_w - 1.5M_c}{W_f}$$ (pg. 84, Baldwin)

Two Test Areas:
High Power Phase → Bring to Boil
Low Power Phase → Maintain Simmer

Lab Procedure: Water Boiling Test (pg. 82-84, Baldwin)

1) Record test conditions, pot/stove dimensions, etc.
2) Weigh a quantity of wood with known moisture content, calorific value, etc.
3) Clean pots, add known quantity of water
4) High Power Phase: Bring water to boil. Record all actions taken.
5) When brought to boil, take out all wood. Knock off charcoal. Weight wood & charcoal. <u>OR</u> Weigh stove before and after burn process to determine wood used.
6) Weigh pot to determine water boiled away.
7) Low Power Phase: Low boil for 30 mins. Record temp each 5 minutes.
8) Weight everything again.
9) Perform calculations.

Other Tests:

- Controlled Cooking Test
  - Standardize ingredients, etc. Cook example of traditional meal. Find SC, PHU.
- Carbon Monoxide
  - Gas Chromatograph (How capture gas?)
  - Use CO Strips – cheap!
- Particulate Matter – Filter Paper (from Kandpal, pg. 436)
  1) SPM collected on glass-fiber filter paper by drawing air through at flowrate of 1.5L/min.
  2) Removed from sampler after 1 hour of operation and kept in a desiccator.
  3) Mass calculated by gravimetric procedure.

Data for the effect of varying design parameters on stove combustion quality, thermal efficiency, pollution emissions, and ease of use would be extremely helpful. If possible, while in Oregon, the following design parameters will be tested.

- Channel gap, length, shape, and fabrication manner
- Grate-to-pot height
- Hole density in grate, material used
- Type of insulation, how it is placed, effect of double walls?
- Primary/Secondary air control
- Type, size, and shape of pots supported
- Use of baffles, different designs
- Chimney designs
- Pot shape and material
- Does changing scale change performance?