# Global Modeling and Testing of Rocket Stove Operating Variations

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# Introduction

*Objective*

This paper presents the results of thermodynamic modeling and testing of a series of rocket stoves developed by Larry Winiarski and Aprovecho Research Center for use in lesser-developed countries. More than 50% of the world's population rely on biomass such as wood, crop residue, or dung as their only source of household energy. Much of this fuel is burnt in inefficient, unventilated stoves and open fires, resulting in deforestation and indoor exposure to toxins in the smoke which cause respiratory and eye disease, cancer, and stillbirths. In fact, acute respiratory infection in Indian children accounts for 2% of the total global burden of disease of all types in all ages. Concerns over these issues have led research teams to develop new models of stoves to provide improved heat transfer to the pans and more complete combustion of the fuel. While use of these stoves has shown considerable improvement over traditional stoves and open fires, there is still room for additional improvement.

The goal of this research is to determine the location and magnitude of heat losses from the series of stoves so that greatest losses can eventually be minimized in design. Ideally, with 100% efficiency, the energy input from the wood should equal the energy transferred to the water. In reality, however, about 90% of this energy input from open fires is lost to the environment. For the rocket stove, this is reduced to about 70%. These losses can be quantified in several main areas: energy lost in the combustion gases, convection and radiation losses from the stove, convection and radiation losses from the pan, energy stored in the stove, and energy stored in the pan. There will also be some other losses not accounted for in the model.

Several important stove design parameters were varied for efficiency and loss comparisons. First, the stove inlet diameter was an important factor to the amount of wood fed into the stove. Second, the chimney height had a drastic impact on the heat radiation from the flames to the pan. Third, the gap between the top of the stove and the bottom of the pan influenced how much heat from the flue gasses and flames was transferred to the pan. Fourth, the amount of insulation in the stove influenced how long it took to heat up the stove and thus affected the efficiency. Finally, use of a skirt around the pan increased heat transfer around the perimeter of the pan. These factors were varied from a baseline setup to examine their effects on stove performance.

*Background Theory*

Fundamental theory of heat and mass transfer and conservation of energy were applied in this analysis. The universal law of conservation of energy states that energy can neither be created nor destroyed:

$$Energy_{In} - Energy_{Out} = Energy_{Change} \quad [1]$$

For the stove, the energy input is based on the energy stored in the fuel wood according to the following:

$$E_{in} = m_f L_f - m_c H_c \quad [2]$$

| | |
|---|---|
| $m_f$ | Mass of wood |
| $L_f$ | Lower heating value of wood, 17500 kJ/kg |
| $m_c$ | Mass of remaining char |
| $H_c$ | Higher heating value of char, 34100 kJ/kg |

The energy out transferred to the water is modeled by:

$$E_{out} = m_w c_p \Delta T + m_e L \quad [3]$$

| | |
|---|---|
| $m_w$ | Initial mass of water |
| $c_p$ | Specific heat of water, 4.185 kJ/kg |
| $\Delta T$ | Change in water temperature from initial to boiling |
| $m_e$ | Mass of water evaporated |
| L | Latent heat of vaporization of water, 2260 kJ/kg |

Since energy can not be created or destroyed, it must change forms in the form of heat transfer. This is by three mechanisms: conduction, convection, and radiation. In this model, conduction losses are negligible as they are accounted for in the change of energy of the stove. Convection and radiation losses may be calculated for both the stove and the pan based on their surface temperatures during combustion. Convection is modeled by Newton's Law of Cooling,

$$q = hA(T_s - T_\infty) \quad [4]$$

| | |
|---|---|
| q | heat transfer |
| h | convective Heat Transfer Coefficient, 20 $W/m^2$ |

| | |
|---|---|
| $A$ | Surface Area |
| $T_s$ | Surface Temperature |
| $T_\infty$ | Ambient Fluid (air) Temperature |

Ratiation is modeled by the Stefan-Boltzmann Law,

$$q = \varepsilon \sigma T_s^4 - \alpha \sigma T_\infty^4 \qquad [5]$$

| | |
|---|---|
| $q$ | heat transfer |
| $\sigma$ | Stefan-Boltzmann constant |
| $\alpha$ | Absorbtivity |
| $\varepsilon$ | Emissivity |
| $T_s$ | Surface Temperature |
| $T_\infty$ | Ambient Fluid (air) Temperature |

Since no energy is created or destroyed within the control volume of the stove and pan, the change in energy term is based only on the energy stored within the mass of the stove and pan. The energy storage terms are based on the specific heat of the materials according to the following equation:

$$\Delta E = m\, c_p\, \Delta T \qquad [6]$$

| | |
|---|---|
| $m$ | Mass |
| $c_p$ | Specific Heat |
| $\Delta T$ | Change in temperature |

These fundamental theories of heat transfer are combined with the law of conservation of energy in order to determine the magnitude and location of the major heat losses from the stove.

$$E_{IN} - E_{OUT} = E_{stoveconv} + E_{stoverad} + E_{panconv} + E_{panrad} + \Delta E_{stove} + \Delta E_{pan} + \Delta E_{diff} \qquad [7]$$

Finally, efficiency is calculated from the simple equation of output over input,

$$\eta = E_{OUT} / E_{IN} \qquad [8]$$

For these purposes, an macro-model will be developed using the aforementioned theory.

## Experimental Apparatus and Procedure

*Experimental Equipment*

### Stoves

Nine subject stoves were made by Ken Goyen, an associate of Aprovecho. The stoves were made out of cold-rolled 24-gauge steel with inlet diameters of 3 inches, 4.5 inches, and 6 inches, each with chimney heights of 6 inches, 9 inches, and 12 inches. The outside diameter of the stove was that of the inlet plus 6 inches. The feed magazines protruded 2 inches from the exterior of the stove, and removable shelves were added to hold the wood.

### Fuel

Kiln-dried 1 X 4 pine was purchased at a local hardware store to ensure maximum dryness and homogeneity of the wood. The wood was then sawed down into suitable-sized pieces for each stove; ½" X ½" for the 3" inlet, ½" X 1" for the 4.5" inlet, and 1" X 1" for the 6" inlet stoves, with lengths varying from about 4 to 10 inches. This was done to keep the size of the wood relative to the stove, a significant operating factor, fairly constant.

### Pans

Two identical aluminum cooking pans were used in all runs. The pans had an 8 inch diameter and height of 5 inches. Both had been used considerably prior to this series, thus had mass differences of about 20 grams, due to the buildup soot on each pan. Before each run, the loose soot on the bottom and sides of the pan was removed using a bristle brush. The pans were always kept uncovered, and each test was run starting with 2 Liters of water.

### Skirts

Both insulated and uninsulated skirts were used for some of the tests. The uninsulated skirt was made two recycled coffee cans riveted together. The gap on this skirt averaged at about ¼". The second was an insulated skirt made of two layers of sheet metal separated by 3/8" of fiberglass insulation in between. The gap on this skirt was varied from almost a flush fit to a gap of about ¼".

### Environment

Tests were conducted in the stove testing area at Aprovecho Research Center in Cottage Grove, Oregon from June through July of 2000. Tarp walls were setup around the covered area to help stop the frequent breezes. Temperature and humidity levels were fairly constant throughout the series.

### Equipment

Equipment used for the tests included:

- Balance – a Nexus mass balance was used to weigh kindling, wood, and remaining charcoal.
- Glass Thermometer – calibrated and used to measure the temperature of water and air.
- Infrared Thermometer – Fluke 65 infrared thermometer wit laser site was used to measure the surface temperatures of the stove and pan
- Data Logger – A Fluke 54II data/temperature logger was used to record the temperatures of the exiting combustion gas and one point on the stove surface throughout the run.
- Air Flow Meter – A Kane-May KM4107 air velocity meter used to measure the flow rate of the air entering the stove.
- PC with Microsoft Excel – A software program was written in Visual Basic for Applications for printing data sheets, analyzing run data, and comparing runs.

## Experimental Procedure

Tests were run not to maximize efficiency or bring the water to a boil rapidly, but to provide operating conditions that were as constant as possible. This allows for accurate comparison of relative efficiencies between stoves. The experimental procedure was as follows:

- Pre-weigh approximately 500 grams of the proper size wood.
- Measure and record the temperature of 2 Liters of water placed in a pot.
- Weigh out approximately 15 grams of newspaper and small pieces of kindling, tear and crumple the paper, and place in the rocket elbow.
- Place 3-4 pieces of wood on the wood holder, light the paper, then start the stopwatch and data logger. The data logger is recording combustion gas exit temperature through a thermocouple placed on the circumference of the chimney exit midway between stove top and pan bottom, and the stove temperature through a thermocouple affixed to the outside of the stove.
- Keep the fire burning with 3-4 pieces of wood at time, pushing the sticks inward as the ends burn off.
- At approximately 30-40 minutes, record the outside temperature of the stove at 8 circumferential and 4 height positions, as well as 4 around the top. Repeat for the pan at 3 height positions and from two thermocouples on the bottom of the pan.
- At about 45 minutes, place an 11-inch extension on the stove inlet, recording the air velocity at 9 to 16 locations, depending on inlet area.
- Record four readings of the percent oxygen in the air leaving the stove.
- Stop adding wood at about 55 minutes, and record the time when the last flame disappears.
- Analyze the data using the “Rocket Stove Analysis” software.

Three tests were run for each of the 9 stove size configurations, using a baseline setup full of perlite, a 1"”gap, and no skirt. Then two tests were run for each height of the mid-sized (4.5” diameter) stove while varying the insulation level, gap, and skirt from the baseline setup.

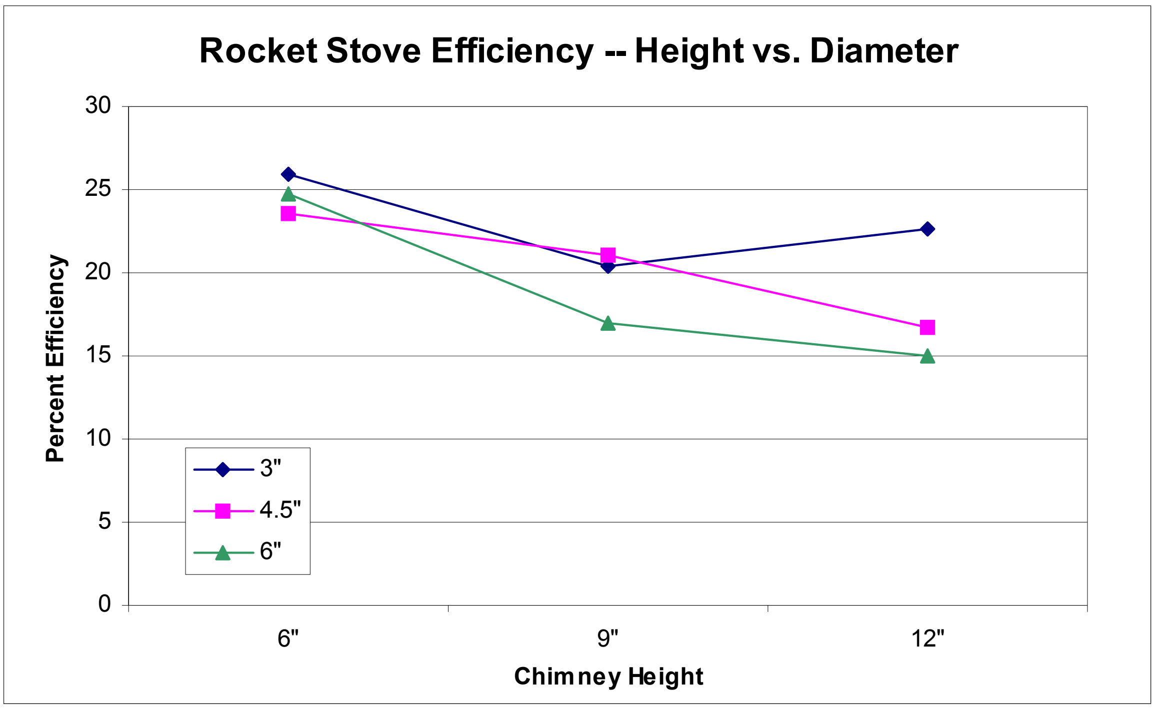
## Results and Discussion

*Efficiency*

Efficiency is essentially the most important factor in designing a stove. An arrangement should be chosen as to maximize the percent of energy released from the wood that is transferred to the water or food.

### Size

The most basic result of this series of three tests per stove shows that smaller inlets and shorter chimneys are more efficient, shown in the following chart:

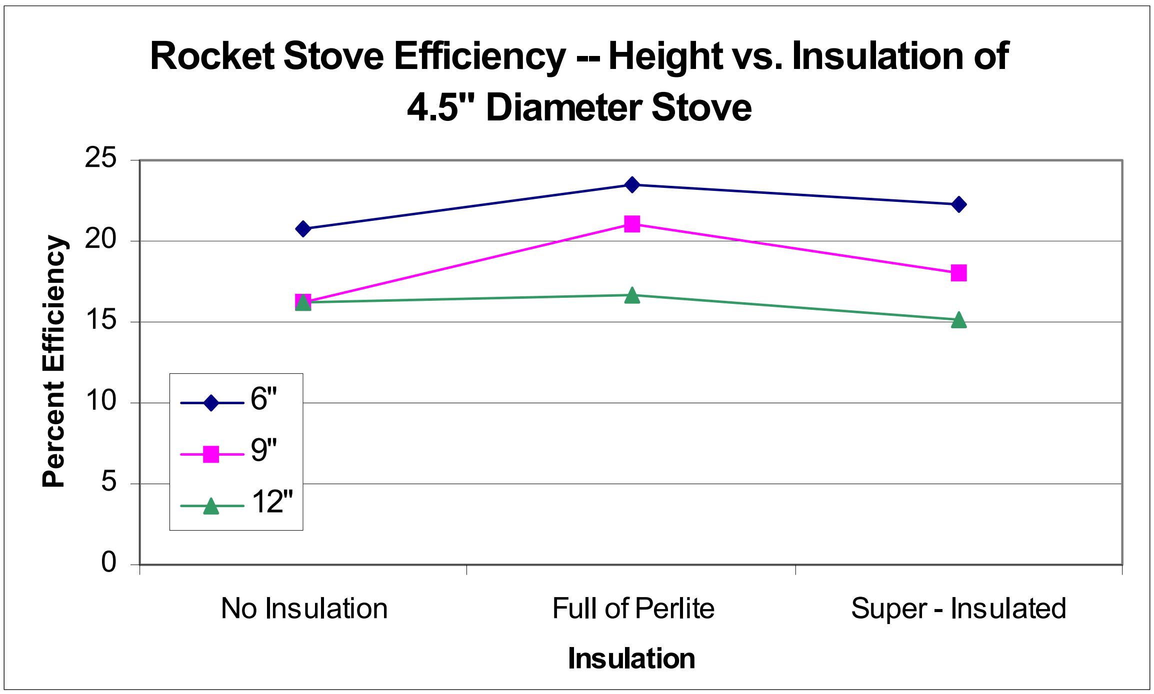



It should be noted that the smaller inlet stoves took a much longer time period to reach boiling than those with larger inlets. Thus while they are technically more efficient, they may not be ideal for field distribution as a stove will not be used if it does not perform according to the users expectations.

## Insulation

An unexpected discovery from these experiments is the effect of insulation on the efficiency of the rocket stove. First, it was shown that adding perlite insulation increases efficiency by about 2 to 5 percent over an uninsulated 4.5" diameter stove. However, super insulating the stove with two layers of fiberglass blanket insulation does not increase efficiency, but instead caused performance to actually decrease by as much as 3% for the 9" high stove. This can be seen in the following chart based on two tests per stove:

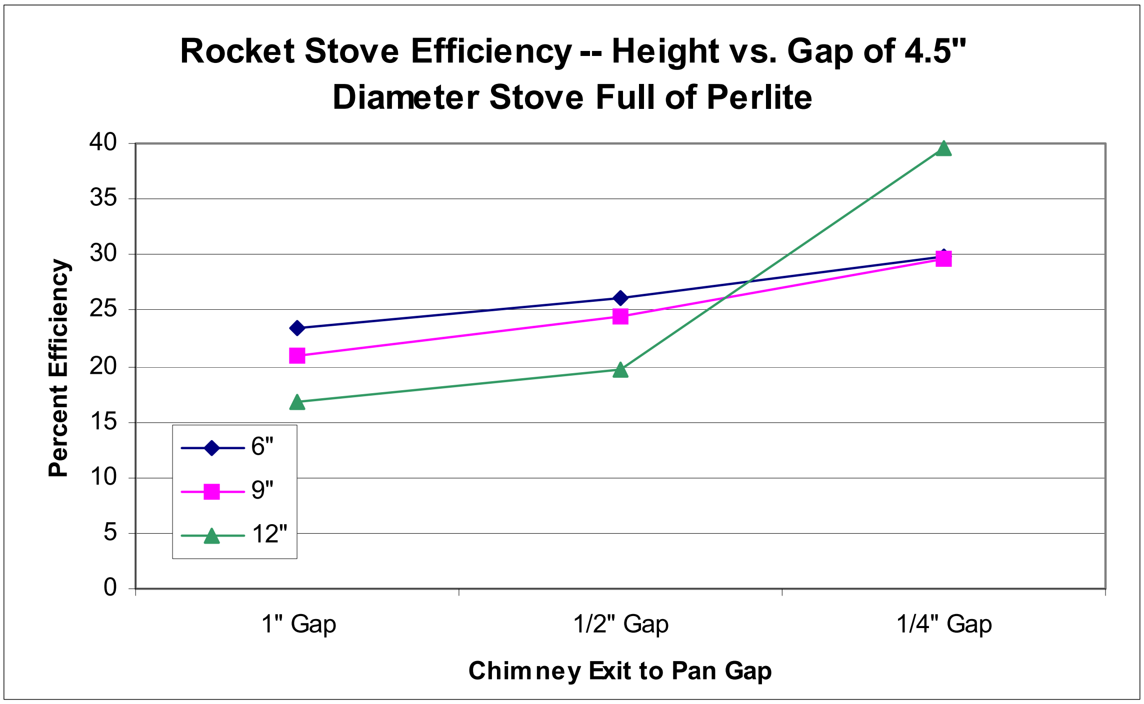
This is most likely due to the fact that adding fiberglass insulation increases the mass of the stove, thus it takes a longer time frame to heat up the stove and insulation. While the stove is heating up, useful heat is transferred to and stored in the stove rather than transferred to the pan and water. This is an important fact




to know since materials more similar to perlite are available locally.

## Gap

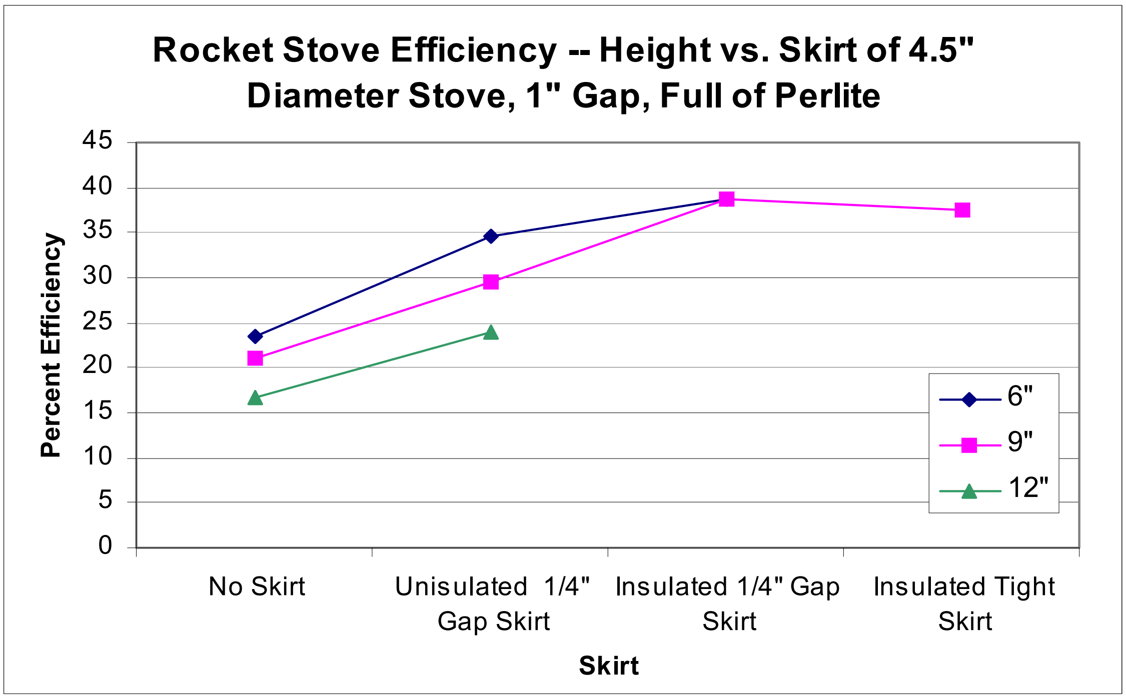
The stove top to pan gap was varied from a standard of 1" down to ½" and then ¼" for comparison on the 4.5" diameter stoves. An almost linear change in efficiency was observed, increasing by about 9% when the gap was reduced from 1" to ¼".




An important consideration, however, is that the ¼" gap sometimes caused the fire to burn out the top front of the feed magazine because not enough air was able to be drawn through the decreased gap to create the proper draft.

## Skirt

Finally, it was shown that use of a skirt has the most profound impact on stove efficiency. The 4.5" diameter stoves with a 1" stove to pan gap were each run first without a skirt, then with a ¼" gap uninsulated skirt, then a ¼" gap insulated skirt, and finally a tight insulated skirt. Addition of the uninsulated skirt caused efficiencies to increase by 10%, and insulating that skirt caused an additional 10% rise! The 9" chimney rose from 21% to 39% simply by use of an insulated skirt.




Use of the tight skirt, however, caused the efficiency to decrease by a few percent because of the problem of a lack of draft space for the exit air.

*Losses*

Heat losses in different forms from different areas of a stove should be minimized in order to maximize the amount of heat transferred to the water. On average for all tests, convection accounted for 77%, radiation for 12%, and storage for 11% of total losses from the stove. For the pan, convection accounted for 92% of the losses, radiation for 6%, and storage for about 2%. Due to the mass and temperature of these components, these proportions seem appropriate.

### Size

As both stove diameter and chimney height increased, both stove and pan losses decreased. Trends in combustion gas loss versus chimney height were not readily apparent, but combustion gas losses did increase with increasing stove diameter.

### Insulation

Stove and pan losses decreased with increasing insulation. Combustion gas losses were greatest in stoves filled with perlite insulation.

### Gap

Stove and pan losses increased with a decreased stove to pan gap, while combustion gas losses decreased.

### Skirt

Losses from the stove, pan and combustion gases decreased with the use of increasing skirt tightness and insulation.

*Oxygen*

The percent oxygen remaining in the combustion gases in the stove is an indicator of the quality of combustion of the stove arrangement. A lower remaining percentage from the atmospheric air of 20.9% indicates more complete combustion and a proper air-fuel ratio. The average percent oxygen for all runs was 14.4%, with a minimum of 4.9% for the 4.5" diameter, 12" height, ¼" gap and maximum of 19.5% for the baseline 3" diameter, 9" height.

### Size

Percent oxygen in the combustion gas decreased with increasing inlet diameter and, in general, increased with increasing chimney height.

### Insulation

Percent oxygen generally decreased with increasing stove insulation, but superinsulation did not show a very significant decrease.

### Gap

Oxygen combustion increased dramatically with a decreased stove to pan gap, linearly from 16.8% to 5.8% for the 4.5” diameter, 9” height stove. This suggests that limiting the draft through the stove provides more efficient combustion.

### Skirt

Similar to the gap, use of a skirt also dramatically decreased the remaining percent oxygen in an approximately linear fashion, from 16.8% without a skirt to 8.7% with the insulated ¼’ gap skirt for the 4.5” X 9” stove.

*Air-Fuel Ratio*

Due to imperfect measurement capabilities, the air-fuel ratio calculations are generally approximate. Generally, the air-fuel ratio should be around 20 for this type of efficient wood combustion. The average for all runs was approximately 45. Deviation from expected is most likely due to difficulty in obtaining precise air flow measurements over the entire duration of the test.

### Size

Generally, the air-fuel ratio increased with increasing stove diameter and increasing chimney height. The minimum was 22.6 and maximum was 116.1.

### Insulation

The air-fuel ratio decreased with increasing insulation, from 39.3 uninsulated to 32.9 superinsulated for the 4.5” X 9” stove.

### Gap

The air fuel ratio also decreased with decreasing stove to pan gap, from 39.9 for the 1” gap to 27.8 for the ¼” gap on the 4.5” X 9” stove.

### Skirt

Use of a skirt with increasing degrees of insulation also decreased the air-fuel ratio.

## Conclusions and Recommendations

This series of fifty tests on varying operating setups of the rocket stove showed the following:

- A smaller inlet diameter results in higher efficiency, lower combustion gas losses, higher stove and pan losses, higher percent oxygen remaining, and lower air-fuel ratios.
- A shorter chimney results in higher efficiency, slightly lower combustion gas losses, higher stove and pan losses, lower percent oxygen, and a lower air-fuel ratio.
- Medium (perlite) insulation provides the highest efficiency and combustion gas losses, while increasing levels of insulation generally decreases stove and pan losses, percent oxygen, and air-fuel ratios.

- Decreasing stove to pan gap increases efficiency, decreases combustion gas losses, increases stove and pan losses, and decreases percent oxygen and air-fuel ratios.
- Use of a skirt with increasing degrees of tightness and insulation increases efficiency, decreases combustion gas losses, decreases stove and pan losses, decreases percent oxygen, and decreases air-fuel ratios.

Thus, an ideal stove theoretically would have a small inlet, short chimney, perlite insulation, a small stove to pan gap, and an insulated skirt to provide maximum efficiency, minimal losses, and complete combustion of the fuel.

## References

Baldwin, Samuel F. Biomass Stoves: Engineering Design, Development, and Dissemination. Virginal: Volunteers in Technical Assistance, 1987.

Bryden, Kenneth Mark.

Bussman, P.J.T. Woodstoves: Theory and Applications in Developing Countries.

Moran, Michael J. and Shapiro, Howard N. Fundamentals of Engineering Thermodynamics, 3rd Edition. New York: John Wiley & Sons, 1996.

Incropera, Frank P. and DeWitt, David P. Fundamentals of Heat and Mass Transfer, 4th Edition. New York: John Wiley & Sons, 1996.

Prasad, Krishna K. and Verhaart, P. Wood Heat for Cooking. Bangalore, Indian Academy of Sciences.