Lab Tests of Fired Clay Stoves, the Economics of Improved Stoves, and Steady State Heat Loss from Massive Stoves

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Ouagadougou, Upper Volta

November 1982

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Foreword

This is the first in what is hoped to be a series of field reports on the work done by the CILSS Regional Woodstoves Technical Coordinator and collaborators following work begun by Dr. Tim Wood. These will not be polished final reports but, rather, represent an effort to get research results into the field quickly in order to aid other ongoing work and to stimulate debate.

No work is done in a vacuum; certainly not the work presented here. Thanks go to: Tim Wood for all of his work at CILSS, his work on stove testing, and his prelimanary work on fired clay stoves; to Mamadou Traore of the Handicapped Artisans Center, Ouagadougou, and Frederic Yerbanga, of Guilougon, for their construction of the fired clay stove prototypes; to G. de Lepeleire for his work on stoves and testing; to S. Joseph and J. Trussell of ITDG for their work on stove testing and on fired clay stoves, including an advisory visit to Upper Volta in 1981; to K. Prasad and all the Eindhoven stove group for their detailed stove testing work; and, finally to G. de Chambre, Bois de Feu, for his assistance with some of the testing. Without the excellent work by these individuals and groups, the work presented here would not be possible.

Finally, apologies must go to all the economists who may be offended by the cavalier treatment of terms and concepts here, and by the imprecision. The intent of the section on economics is to stimulate economists into taking a hard look at the economics of improved stoves and to develop some guidelines for their development. It is also hoped that this section will make field workers sensitive to some of the economic questions their stove work poses.

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INTRODUCTION AND OVERVIEW

This report is comprised of three separate sections: a description of ongoing lab testing of fired clay stoves and a discussion of test results to date; an analysis of the economics of improved stoves; and a calculation of the effect of wall thickness on heat loss from massive stoves.

The first section describes the fired clay stoves tested, the test methodology used, and the results obtained. Though there were a number of methodological problems with variations in wind, wood moisture content, and between different operators, the stoves uniformly performed well. In comparison to a three stone fire with a Percentage of Heat Utilized (PHU) of 11.5±1.9%, every fired clay stove tested was found to have a PHU of 22% or more--double that of the open fire. The best fired clay stove had a PHU of 36.7±1.5%. Though these laboratory PHU test results cannot be compared to wood economies in the field, these results are encouraging. Details of the effect of grills, grill height, secondary air and shielding the pot with a high stove wall are contained in the text.

In comparison to massive stoves, fired clay stoves have a number of advantages and, potentially, some serious disadvantages:

Efficiency: In the laboratory tests presented here, the fired clay stoves showed higher efficiency than any known tests on massive stoves (massive stoves typically show PHUs in the range of 15 to 20% for models with chimneys and roughly 18 to 23% for chimneyless models). There are several reasons for this. First, the one pot fired clay stoves tested here provided for the hot gases to escape around the pot, effectively increasing the surface area for heat exchnge. Massive stoves with chimneys provide little surface for heat exchange to any of the pots (this is often made worse by building the stove top surface thicker than necessary. As a result (in part), the second pot does not heat sufficiently and is sometimes left open by the women who use the stove. Chimneyless models perform better, as the second pot does have more heat exchange area with the hot gases. Second, combustion is probably better in the fired clay stoves tested as compared to massive stoves, since both a grill and secondary air were provided. Massive stoves typically allow air entry only through the door, which is often so clogged with wood that not enough air can enter for good combustion to take place.

Cost: The fired clay stoves tested here can be produced for less than 1,000 CFA (US$ 1=350 CFA). The village pottery industry in the Sahel can produce large water storage jars for 300 to 400 CFA, and it is likely that the price of a stove can ultimately be lowered to the same range. By comparison, massive cement stoves cost roughly 5,000 CFA.

Production: Fired clay stoves have several advantages over massive stoves in terms of production. First, they can be produced more rapidly--perhaps 20 clay stoves can be produced per day by a potter, compared to three or fewer massive stoves per day by a mason. Second, potential clay stove production facilities are already in place throughout the Sahel. Third, no imported materials are needed.

Quality Control: A recurring problem with massive stoves is the quality of their construction. The performance of a massive stove is fairly sensitive to the accuracy of its internal dimensions. When individual families themselves construct the stove (and thereby avoid the cost of a professional stove builder), performance sometimes suffers. Even those stoves built by professional stove builders sometimes show poor construction if there is a long time lag between the mason's training session and the stove's construction. As fired clay stoves can be mass produced, formed on molds and, according to lab results, apparently perform well regardless of form (though some certainly perform better than others), it is believed that problems of quality control can be considerably reduced.

Portability: In poor urban areas families frequently move, and massive stoves are large investments that cannot be taken along. Clay stoves, however, are easily portable and may, thus, be preferred under these conditions.

Stability: Fired clay stoves are not as stable as massive stoves. This may be a serious drawback.

Lifetime: Though fired clay resists rain well (an ongoing problem for banco stoves), it may well prove very fragile in the demanding environment of daily use. Reinforcement with metal or other materials may be necessary--to support the pot and the fired clay for the firebox, and to generally reduce heat loss.

Health: The types of fired clay stoves presented here do not evacuate smoke (part of the reason for their high efficieny) and thus do not provide the health benefits that a massive stove with a chimney provides.

Social Acceptability: Many portable metal stoves have already gained acceptance in the major cities, as have massive stoves.

Section II is a brief look at the economics of improved stoves. The calculations in this section are idealized and use only crude estimates of the actual values of stove cost, lifetime, efficiency, wood costs, and effective interest rates. The intent of this calculation is not to support or detract from stoves generally or any genre of stoves in particular; it is intended to stimulate debate among people working on stoves, to interest economists to do detailed calculations with more legitimate parameters of stove economy, and to provide a focus for data collection for the more detailed calculations sure to come.

The calculation itself suggests that massive, high investment stoves are economic for their owners only where wood costs are very high. Even then, the economics are very sensitive to the stove's efficiency, initial cost, lifetime, and daily wood cost. Outside of urban areas where wood costs are lower, the economic rate of return on a stove diminishes rapidly with wood cost.

The third section discusses the steady state heat loss from massive stoves. In a highly idealized calculation it is shown that in special conditions, such as when the air around a stove is calm, the heat loss from a stove actually increases with the thickness of the walls. In the more general case it is shown that heat loss is reduced only slightly by large increases in stove wall thickness. Thus, thicker stove walls do not significantly help reduce heat loss from a stove, and can (insignificantly) increase heat loss. This, together with the additional cost and effort of constructing a thicker wall and with the longer warm-up times, suggests that stove walls should be made no thicker than necessary, typically 10 cm, to provide the needed strength and stability for a long life.

I. LAB TESTING OF FIRED CLAY STOVES

Presented in this section are:

- the design of the stoves tested;
- the test methodology, method of calculating efficiency, and a brief error analysis;
- a brief discussion of the problems observed with the tests both individually and generally;
- the results of the lab tests;
- an analysis of lab test results; and
- some conclusions and discussion of future work.

The Design of the Stoves Tested

A traditional three stone "stove" and five one-pot fired clay stoves were tested in simulated cooking tests. Two nearly identical pots were used interchangeably for the tests.

The lab tests on the three stone stove provided a reference value of stove efficiency. A variety of parameters were used in the fired clay stoves to observe their effect on overall efficiency. The stoves and pots are described in detail on the following pages. In brief, the tests crudely determined the effect on efficiency of: 1) restricting air entry into the stoves; 2) a grill and secondary air to improve combustion; 3) the distance between grill and pot; and 4) the effective heat transfer area of the pot.

It must be noted in examining the stove designs that the values for the dimensions are not very precise: edges are rounded, making difficult a determination of where a certain feature starts or stops; wall thicknesses vary; and, firing warps the form of the stove so that even forms shaped on a potters wheel do not remain constant, e.g. have a constant diameter. Some of these imprecisions are noted on the following pages. In addition, the drawings of the stoves and marmites (pots) are not to scale, but are only illustrative.

Summary of stove dimensions and variations are given in chart form on the next page.

SUMMARY OF STOVE DIMENSIONS* (in cm)

Feature	B	C	D	E	F
Base outside diameter	22	22	23	23	23
Total hight	19	19	22	21.5	26
Top outside diameter	31	35	30	30	30
Grill?	no	no	yes	yes	yes
Width of door	16	12	11.5	11	10
Height of door	11	10	7.5	8.5	9
Side vents	4	2	0	0	0
Secondary air?	no	no	yes	yes	yes
Height between pot and stove bottom (with grill lowered)	11	8	10	6.5 (10.)	6 (9.5)
Height of pot exposed above top of stove	13	11	13	11	6
Stove wall contoured to pot?	no	no	yes	yes	yes
Wall thickness	2	2	1	1	1

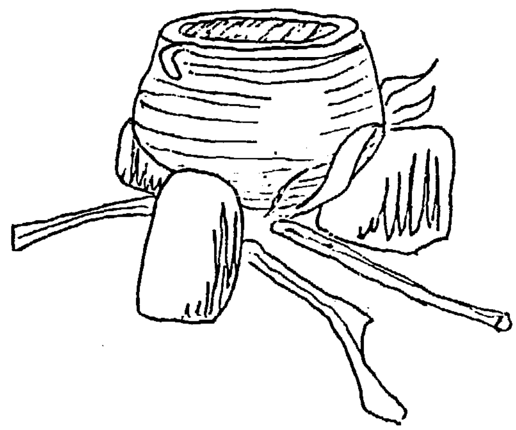
SUMMARY OF STOVE VARIATIONS*

Feature	B	C	D	E	F
Air access:					
Door only	B2	C2	D4		
Door and side vents	B1	C1			
Door and grill only			D3	E3,4	F3,4
Door and secondary only			D2	E6	
Door, grill, and secondary			D1	E1,2,5	F1,2
Grill height:					
Grill to pot--6 cm				E1,2	F1,3
Grill to pot--10 cm				E2,4	F2,4
Wall height				E vs. F	

* More details are given in the stove design descriptions which follow.

STOVE A: Traditional "three stone" fire

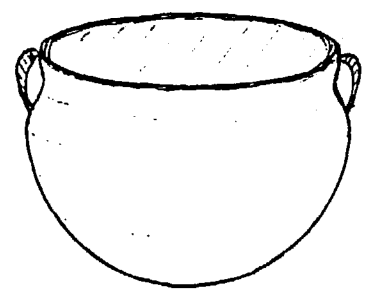
Description: Three rocks are placed on a concrete slab to support the pot. The firebed diameter is as great as 20 cm, and the pot bottom is roughly 10 cm above the concrete slab.



Variations: A1--As shown*

POT ("marmite"):

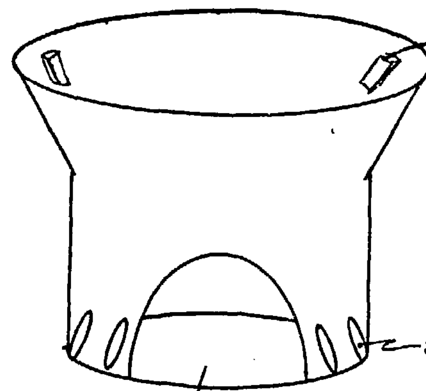
Description: The pot used is made of aluminum and has a top diameter of 24.5 cm, maximum diameter of 26.5 cm, and total height of 19 cm. The height from the pot's bottom to its maximum diameter is 10 cm. Its weight is roughly 1.28 kg, and its volume is 7.8 litres. The second pot used has the same dimensions and weighs 1.58 kgs.



Variations: The two pots were used interchangeably except in stove F, where the very slight variation in dimensions prevented the heavier pot from entering the stove opening and seating properly.

*Diagram traced from De Lepeleire

STOVE B

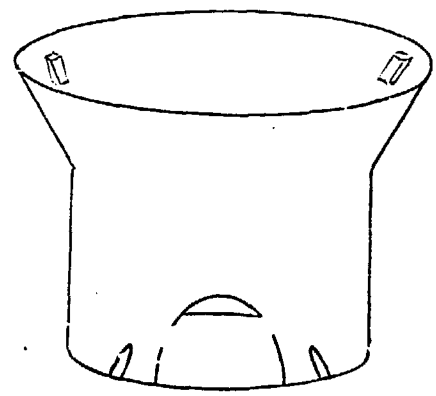


Description: This stove is made of fired clay, with 2 cm thick walls throughout. Stove height is 19 cm. The outer diameter of the base is 22 cm. The walls are vertical to the flare, a distance (outside measure) of 14 cm from the bottom. Top outside diameter is 31 cm. There are three pot supports just inside the top flare, each 0.5 cm thick, 5.5 cm long, and 2.5 cm wide. The door is a rounded trapezoid 11 cm high, 16 cm wide at the base, and roughly 10 cm wide at the top. Air holes on each side of the door are 5 cm high, 1.5 cm wide, and cut at an angle both vertically and to the perpendicular from the stove surface; vertically the first pair of holes begins 4 cm from the bottom of the door (adjacent edge to adjacent edge) and end 3 cm from the door. The second pair of holes begins 11 cm away from the door and ends 10 cm away at their top. The holes are cut at an angle from the perpendicular to the stove body toward the door. The bottom of the stove is solid. The pot rests within the flare, 0.5 cm from the stove wall at closest approach (determined by the pot support thickness) and 11 cm from the bottom of the stove (outside bottom of the pot to inside bottom of the stove bottom); roughly 13 cm of the pot lie above the top of the stove.

Discussion: The flared top can adjust to a wide range of pot sizes, though the variation of efficiency with pot size has not yet been tested. The pot supports determine the minimum width of the channel for gases to pass by the pot. The air holes beside the door provide additional air to improve combustion at the rear of the stove; cutting air holes at an angle to the stove body perpendicular reduces the effect of winds blowing from the side.

Variations: B1--as shown
B2--all four air holes closed

STOVE C



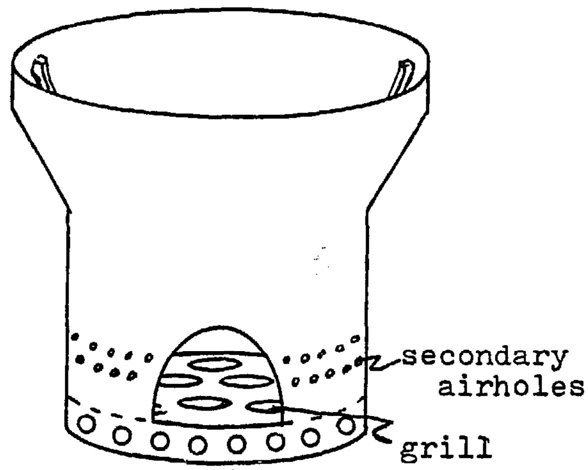
Description: Made of fired clay and basically of the same form as Stove B. Height is 19 cm; bottom outside diameter is 22 cm; distance from bottom to flare is 12 cm (outside measure); top outside diameter is 35 cm. As before, walls throughout are 2 cm thick. The door is elliptical with a base width of 12 cm and a height of 10 cm. Pot supports are basically the same form and dimension as for stove B, but, in this case, because of some warping during firing, the top is not perfectly round and the distance between the pot and stove walls varies from contact to 1.5-2.0 cm at closest approach. There is only one pair of air holes, the same dimension as for B, each tilted toward the door. The distance from the bottom edge of the door to the near bottom edge of the air hole is 12 cm, and the distance to the top near edge of the air hole is 10 cm. With the pot in place, the distance between the inside bottom of the stove and the outside bottom of the pot is 8 cm. Eleven cm of the pot is exposed above the top of the stove. The bottom is solid.

Discussion: This stove was designed to see if a smaller door than in Stove B would reduce heat loss. Only one pair of holes was thought necessary. In B it was felt that the inside pair of holes probably didn't contribute much air to the rear of the stove, beyond that provided by the door.

Variations: C1--as shown
C2--both air holes closed

STOVE D

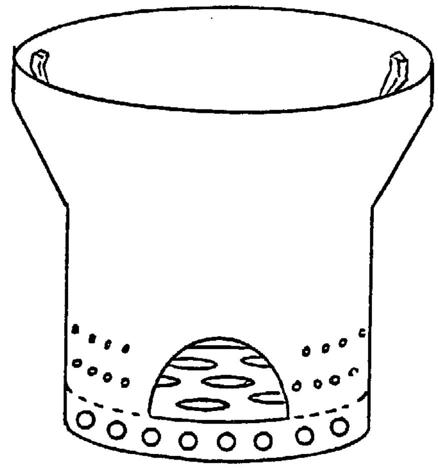
Description: Stove D is fundamentally different from Stoves B and C in that it has a grill, holes for secondary air to enter the firebox, and does not flare continuously at the top. Instead it follows (crudely) the contour of the pot. The grill is fixed in place and cannot be moved. The entire stove is made of fired clay, with walls roughly 1 cm thick throughout. The bottom outside diameter is 23 cm; total height is 22 cm; and top outside diameter is 30 cm. There are 20 holes of 1.5 cm diameter in the base of the stove which provide air to the space below the grill. These holes are equally spaced all the way around the stove. The distance from the bottom of the base to the bottom of the grill is 3.5 cm. The grill is 1 cm thick and has 13 holes of 1.5 cm diameter. The door is elliptical, width a base width of 11.5 cm and a peak height of 7.5 cm. Secondary air holes are evenly spaced around the stove body in two staggered lines. The first line consists of 16 holes of 0.8 cm diameter, 2.5 cm above the top of the grill; the second consists of 17 0.8 cm diameter holes, 5.5 cm above the top of the grill. Walls are vertical from the bottom of the base for 13 cm to the beginning of the flare, and then again from the top of the flare 19 cm above the base to the top of the stove. Pot supports are similar to those for B and C, but curved to fit the wall. The pot rests roughly 1 cm from the stove wall at closest approach. The distance between the top of the grill to the bottom of the pot is 10 cm, and 13 cm of the pot are exposed above the top of the stove.



Discussion: This stove was designed to provide data on the importance of primary and secondary air for combustion and stove efficiency. The amount of primary and secondary air can be varied as desired, as can the placement of the secondary air holes. Due to the time consuming nature of these tests, only "air on" and "air off" measurements were made.

Variations: D1--primary air open, secondary air open
D2--primary air closed, secondary air open
D3--primary air open, secondary air closed
D4--primary air closed, secondary air closed

STOVE E

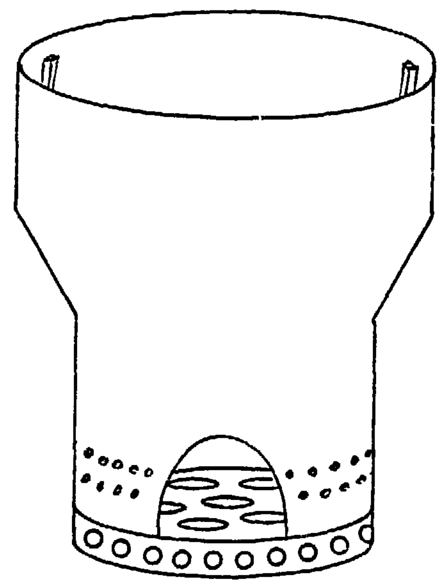


Description: Stove E is basically the same form as stove D, except that the grill is not fixed in place. The outside diameter (O.D.) of the base is 23 cm. The base has 18 holes of 1.5 cm diameter in it to let air enter the space below the grill. The distance from the bottom of the base to the top of the grill is 6.5 cm. The grill is 1 cm thick and has 19 holes of 1.5 cm diameter. The door is nearly square and is 11 cm wide and 8.5 cm high. Secondary air is provided by two parallel staggered lines of 0.8 cm diameter holes: the lower 16 holes are 3 cm above the grill; the second 15 holes are 5 cm above the grill. The distance from the bottom of the base to the start of the flare is 13 cm. The flare continues vertically 6 cm, and then the wall rises vertically again for the final 2.5 cm. Total height is 21.5 cm. The top outside diameter is nominally 30 cm, although warping during firing created some ripples in the top O.D., reducing the O.D. to 29 cm in one place. Pot supports are similar to the previous ones. With the grill in place as designed, the distance from the top of the grill to the bottom of the pot is 6.5 cm. The grill is supported by three supports attached to the stove body, each 9 cm long (around the stove body), 3 cm wide (from the stove body toward the stove center) and 1.5 cm thick. When the grill is placed just below the grill supports, the distance between the top of the grill to the bottom of the pot is 10 cm. In either position roughly 11 cm of the pot are exposed above the top of the stove.

Discussion: This stove, as Stove D, was designed to determine the effect of the grill height. It was found that this form had the advantage of being easier to fire than the type with a fixed grill; the fixed grill tended to crack in the kiln, perhaps because poor air circulation results in varied contractions during firing. A problem with this stove was that although the grill could be lowered, the position of the secondary air holes could not be changed. Lowering the grill should, in principal, change the combustion processes in addition to affecting the proximity of the pot to the fire. Similarly, the door was fixed, and with the grill placed lower, the wood entered at an angle which partially negated the effect of lowering the grill.

Variations: E1--grill in place, primary air open, secondary air open
E2--grill lowered, primary open, secondary open
E3--grill in place, primary open, secondary closed
E4--grill lowered, primary open, secondary closed
E5--grill low, primary open, upper half secondary closed
E6--grill in place, primary closed, secondary open

STOVE F



Description: Stove F is similar to stove E, except that it has a higher wall which encloses the pot more completely. The walls are roughly 1 cm thick throughout. The base has an O.D. of 23 cm and 17 evenly spaced holes of 1.5 cm diameter to provide air to the space below the grill. The distance from the bottom of the base to the top of the grill is 7 cm. The grill is 1 cm thick and has 19 1.5 cm holes in it. The grill is supported by three protrusions from the stove body which follow the curve of the stove body and are 9 cm long, 3 cm wide and 1.5 cm thick, exactly as in stove E. The door is nearly square--10 cm wide and 9 cm high--and begins 1 cm below the grill when the grill is in place. Secondary air is provided by two parallel staggered lines of 0.8 cm diameter holes: the lower having 16 holes 3 cm above the grill (when in place), and the upper 15 holes 5 cm above the top of the grill. The stove walls are vertical from the bottom of the base 13 cm to the start of the flare and again from the top of the flare, 19 cm above the base, to the top of the stove--26 cm high total. The O.D. of the top is roughly 30 cm, with 0.5 cm of ripple to either side. Pot supports are the same as before. The pot bottom rests 6 cm above the top of the grill when the grill is in place, or 9.5 cm above when the grill is placed immediately below its supports. When in place, just 6 cm of the pot are exposed above the top edge of the stove.

Discussion: This stove was designed in order to observe the effect of the higher wall on stove efficiency as compared to stove E. All other factors are nearly identical. The higher wall was expected both to reduce heat loss from the pot to the environment, and to provide considerably more "channel" for heat transfer between the hot gases and the pot. Similar problems as in stove E were found with respect to the change of position of the grill and the fixed position of the door and secondary air holes. Also, it was difficult to construct the additional height of the wall on a potters wheel. Molds should pose no problems.

Variations: F1--grill in place, secondary air open
F2--grill lowered, secondary open
F3--grill in place, secondary closed
F4--grill low, secondary closed

Test Methodology

The methodology used generally followed the draft procedure developed by the "Working group meeting on a woodstove field test standard, Marseille, 12-14 May 1982", and by Tim Wood. A sample test sheet follows the testing procedure described below.

The testing procedure listed here roughly follows that of Tim Wood.

1. Stove and area around are is swept clean of ashes and other debris. Stoves are felt to make sure they are cool. Because of their very low thermal mass, cooling generally takes no more than 30 minutes.

2. Weather conditions, particularly wind, are noted.

3. Wood is chopped into pieces roughly 2 cm by 2 cm by perhaps 20 cm long, along with a number of smaller pieces to start the fire. All wood, including kindling, is then weighed and set to the side of the stove. A smaller amount is withdrawn from this pile and separately weighed and used to start the fire. Any wood that enters the fire is weighed and recorded separately in addition to the overall wood weights. This provides a check that wood is not misplaced during the test.

4. The pot to be used is weighed on scales accurate to 10 gm over 5 kg, and the weight recorded. Approximately 3 kg of water are added to the pot and the total weight of pot plus water is recorded.

   The same pots and same balance tray are used each time, and their weights are well known. Nevertheless, they are carefully weighed each time so that, first of all, changes in the balance performance can be quickly spotted, and second, so that an analysis of all the readings will provide a rough error analysis and estimate of the balance's precision.

5. The wood is then arranged in the stove, a small (1 ml or so) amount of kerosene added to the wood, and the wood set on fire. While the fire becomes established, (a minute or so) the water temperature is taken. When the fire is burning well, the pot is placed on the stove, and a stopwatch is started.

6. The temperature of the water is recorded every five minutes until the water begins boiling. The wood is pushed in, or added (after weighing and recording) in order to maintain a reasonably steady but not excessivley large fire. Different testers vary dramatically in their attitude as to what constitutes a reasonably steady and not excessively large fire. (This variation was reduced by attempting to ensure that a tester tested each stove the same number of times.) Obsevations such as the color and extent of smoke, the effect of the wind on the stove, or flames shooting out the door or stove top are recorded.

7. As soon as the water starts to boil the flames are blown out; the wood left in the stove is weighed and recorded; the total amount of wood remaining is weighed and recorded; and the pot is weighed and its weight recorded. The amount of charcoal in the stove is neither weighed nor estimated. (It was found to be too disruptive to sweep up the charcoal in the stove and on the ground below, weigh it, and put everything back together for the second phase of the test--the pot cooled excessively and the fire was more difficult to restart. In those cases where the pot refused to come to a boil, i.e., where it would stay at a temperature of 90°C for more than 15 minutes, the first part of the test would be ended as just described, and the second part started as though the first had been successfully completed.)

8. No lids of any sort are used during any part of the test. The pots remain completely uncovered throughout.

9. After all wood and pot weights are taken and recorded, a small amount of wood is again taken from the larger pile, weighed, and added to the stove. The fire is relit, the water temperature recorded, the pot of water returned to the stove, and timing begun again.

10. Temperatures are again recorded every five minutes (during a number of tests only every ten minutes). The fire is maintained at a steady level, to keep the water temperature above 90°C but below a vigorous boil. (In several cases the temperature dipped below 90°C; this was ignored in calculating the stove efficiency or deciding whether or not to include the data. Again lids were not used on the pots.)

11. After 60 minutes the fire is again blown out, the weight of the wood remaining in the stove recorded, the total remaining wood weight recorded, the pot weight recorded, and the weight of the charcoal remaining after the test recorded.

<u>**Calculating the Percent Heat Utilized**</u>

The procedure for calculating the percent heat utilized (PHU) was essentially identical to that used by Tim Wood. The formula used was :

$$\text{PHU} = \frac{\text{(Change in water temperature) x (initial weight of water) x 4.184 + (weight of water evaporated) x 2,260}}{\text{(weight of wood burned) x 18,000 + (weight of charcoal) x 29,000}}$$

All weights are given in kilograms and all temperatures are given in centigrade. Note that the thermal capacity of aluminum is ignored, as it is small.

As noted by Wood, this calculation contains some implicit assumptions:

SAMPLE LABORATORY TEST DATA SHEET

Test Number ______________ Date ______________

Name of tester ______________ Weather conditions ______________

Pot used ______________ Time ______________

Stove ______________

START:

Weight of pot ______________ Weight of pot w/water ______________

Weight of balance tray ______________

Weight of balance tray with wood ______________

BOILING TEST:

Time	Elapsed time	Water Temperature	Weight of Wood added to fire	Remarks
	0			
	5			
	10			
	15			
	20			
	25			
	30			
	35			
	40			
	45			

Weight of the balance tray and wood remaining in the stove ______________

Total weight of unused wood and the balance tray ______________

Weight of the pot and water ______________

SIMMERING TEST:

Time	Elapsed time	Water Temperature	Weight of Wood added to fire	Remarks
____	0	____	____	____
____	5	____	____	____
____	10	____	____	____
____	15	____	____	____
____	20	____	____	____
____	25	____	____	____
____	30	____	____	____
____	35	____	____	____
____	40	____	____	____
____	45	____	____	____
____	50	____	____	____
____	55	____	____	____
____	60	____	____	____

Weight of the balance tray and wood remaining in the stove ____________

Total weight of unused wood and the balance tray ________________

Weight of the charcoal remaining and the balance tray ______________

Weight of the pot and water ______________________________

REMARKS:

- It assumes, with little error, that the latent heat of evaporation of water is 2,260 J/g and that the specific heat of water is 4.184 J/gm°C.

- Much less justifiable are the assumptions that the heat values of wood and charcoal are 18,000 J/g and 29,000 J/g respectively. This was not verified during the course of these tests, and it is clear from the tests that the moisture content of wood, which affects the calorific value for wood given above, did vary significantly during the tests. This will be discussed in greater detail later on.

In the following data and analysis, three different PHUs are calculated: the PHU to bring the water to a boil, the PHU of simmering the water for one hour, and the average PHU for these two parts.

The PHU for bringing the water to a boil was calculated from the measurements made in steps 3, 4, 5, and 7 above. The change in water temperature is that from the moment the test begins to the boiling temperature; initial weight of water is that recorded in step 4 (minus pot weight); the weight of water evaporated is the difference in the weight of the pot from step 4 to step 7; the weight of wood burned is the difference in total wood weight between steps 3 and 7; and the charcoal weight used is one half the weight measured in step 11.

The PHU for simmering the water for one hour is calculated similarly. In this case the change in water temperature is the difference between the water temperature recorded at the beginning of step 10 and the boiling temperature; initial weight of water is that recorded in step 7; weight of water evaporated is the difference in weight of the pot between steps 7 and 11; the weight of wood burned is the difference in total wood weight from step 7 to 11; and the charcoal weight is one half that recorded in step 11.

The average PHU uses the change in water temperature from step 5 to boiling; the initial weight of water from step 4; the weight of water evaporated from the difference in pot weights between steps 4 and 11; the weight of wood burned is the difference in total wood weight from step 3 to step 11; and the weight of charcoal is that measured in step 11.

Although the charcoal is weighed only once and its weight is divided between the boiling and simmering stages of the test in calculating the PHU, it is likely that the charcoal is established mostly during the first stage (boiling) and a steady state condition reached during the second stage. Dividing it equally between the two stages will then tend to understate the first half PHU and overstate the second half PHU.

Also note that in calculating the average PHU, the energy to reheat the water is not included (i.e. the heat required to raise the water temperature from its value at the beginning of step 10 to boiling). The reason for this is that the major heat loss mechanism cooling the pot between the two stages of the test is probably evaporation. To include reheating here would be, in a sense, a form of double counting in that case.

Error Analysis

A brief but crude estimate of the internal errors in these PHU calculations can be easily made. First, though the balance is rated at ±10 gr in 5 kg, we can estimate its precision by looking at the mean and standard deviation of the weighing of the balance pan--repeated weighing of the same quantity. Reviewing the data sheets we find:

Weight	Entries
0.640	9
0.645	4
0.650	45
0.655	8
0.660	25
0.665	1

giving an average of 0.652 and a standard sample deviation of 0.00621.

We can do the same for the weight recorded on the data sheets for the pot. Examining the entries for the lighter pot we find an average weight of 1.283 kgs with a sample standard deviation of 0.00769. It should be noted here that although the pots were scrubbed before each test to prevent buildup of soot, they were not allowed to dry thoroughly, which would tend to scatter the data and weight it slightly upwards.

Here we will assume a balance precision of ±8 gms based on the above calculated standard deviations. We will also arbitrarily choose the thermometer error to be ±1°C simply based on personal experience with these small mercury thermometers.

Choosing representative values for an average PHU calculation we find the PHU given by:

$$PHU = \frac{4.184WT + 2,260.E}{18,000 \pm x)F - (29,000 \pm y)C}$$

where,

$W=(4.28 \pm 0.008)-(1.28 \pm 0.008)$

$T=(98 \pm 1)-(28 \pm 1)$

$E=(4.28 \pm 0.008)-(2.93 \pm 0.008)$

$F=(2.55 \pm 0.008)-1.65 \pm 0.008)$

$C=(0.71 \pm 0.008)-(0.65 \pm 0.008)$

Now we note in Brownlee that the variance of the sum of two variables equals the sum of their two variances (for uncorrelated variables). From this we conclude, crudely, that the standard deviation of the sum (or difference) of two variables is approximately 1.4 times the standard deviation of one (assuming the standard deviations are equal, then because the variance is the square of the standard deviation--with some factors of n--we find the standard deviation of their sum equal to 2 1/2 times the standard deviation of either one of the variables). Thus, we find, normalizing the values:

$$\mathrm{PHU} = \frac{3.0(1\pm0.004)70(1\pm0.02)4.184 + 1.35(1\pm0.009)2{,}260}{0.9(1\pm0.013)18{,}000(1\pm x) - 0.06(1\pm0.02)29{,}000(1\pm y)}$$

or, ignoring the unknown factors in the calorific value of wood and charcoal, x and y,

$$\mathrm{PHU} = \frac{878(1\pm0.024) + 3{,}050(1\pm.009)}{16{,}200(1\pm.013)-1{,}740)1\pm0.2)}$$

and changing the PHU to a percentage, we find

$$\mathrm{PHU} = 27(1\pm0.051)\% \text{ or } 27\pm1.4\%$$

It is interesting to note that even though the thermometer has a very large error by itself, it contributes only 15% of the above error of 0.051 because of the large size of the evaporation term 3,050(1±.009) above. The largest single contributor to the above error is the charcoal term, because of the large factor, 29,000, by which it is multiplied. It alone contributes 48% of the total 0.051 error. It is likely, however, that all these sources of error are quite small compared to the uncertainty in the calorific value of wood or charcoal.

In addition to the above internal errors, there were several problems with the test methodology:

1. Wind: The experiments were begun in an open courtyard. It was quickly determined that the wind was sufficiently variable and sufficiently strong to scatter the test results. Thus, after test 25 a wall was erected around each test site. Each wall was 80 cm high and in the shape of a "U" 70 cm wide and 110 cm deep. The open end of the U faced a three story building roughly 200 cm away, reducing wind from that direction to essentially zero. Nevertheless, crosswinds were observed to disturb the stoves even with the wall, but significantly less than without.

2. Wood moisture content: The wood moisture content was observably variable by the manner in which it burned. Tests were done at the end of the rainy season and well dried wood was impossible to buy. To overcome this, after test 50 all wood was kept in clear polyethylene tubes 30 cm diameter and 2 meters long for roughly one week before use. These tubes full of wood were left in the sun and tilted at an angle of

roughly 10 degrees to both heat the wood and provide a small air current (through the thermosyphon effect) to remove the moisture from the wood. Internal temperatures at midday were roughly 10°C above ambient. Flaps at the ends of the tubes were left hanging to prevent the rain from entering. Wood moisture content, however, was not measured and is not known, but should be reasonably uniform after test 50. The type of species used was likewise not controlled. This, however, is probably much less important than the wood moisture content.

3. Order of tests: The order of the tests was not strictly controlled at the start of the program, with the result that certain types of stoves and certain variations--stoves B and C in particular--were tested too frequently during the first 25 or so tests and not frequently enough during the following 25 to 30 tests. Because factors such as wind and wood moisture content were being simultaneously brought under better control, there is some bias against these stoves.

4. Operators: Each tester tested differently, i.e. controlled the fire differently, maintained a different temperature during simmering, etc. It was attempted, though not entirely successfully, to have a tester test each stove the same number of times to reduce this bias.

A number of problems were observed in individual tests:

Test Number	Problem
17	Stopped after first half on account of darkness
18	Test sheet lost
19	Test sheet lost
20	Wood weighings inconsistent
21	Wood weighings inconsistent
26	Second half not done
28	125 minutes without boiling, 35 minutes at a temperature between 90° and 95°
31	Inconsistent wood weighings
36	First half took 90 minutes, second half not done
49	Inconsistent wood weighings
58	Inconsistent wood weighings
94a	Incomplete due to rain
105	Forgot to record measurements between the two halves
108	Rained out of second half

Results for all the lab tests appear in chart form beginning on the next page. A key to abbreviations used follows the chart.

TEST RESULTS

Test #	Stov	Pot wt.	H20 wt. boil	H20 wt. simr	H20 evap boil	H20 evap simr	Fuel wt. boil	Fuel wt. simr	Char coal wt.	Strt Temp boil	Boil Temp	Strt Temp simr	Mnts to boil	Burn Rate boil	Burn Rate simr	Effc boil	Effc simr	Effc ave.
1	E1	1.29	3.38	3.04	0.34	1.38	0.45	0.79	0.06	29	97	76	30	15.	13.	24	24	24
2	B1	1.22	3.11	2.79	0.32	1.12	0.39	0.67	0.07	28	96	70	35	11.	11.	27	25	24
3	E4	1.27	3.10	2.80	0.30	1.22	0.46	0.66	0.07	28	96	79	36	14.	11.	22	27	24
4	B1	1.57	3.26	2.78	0.49	1.08	0.58	0.75	0.07	32	96	74	64	9.1	12.	21	22	20
5	D1	1.28	2.92	2.54	0.38	1.01	0.49	0.49	0.03	32	96	79	49	10.	8.2	20	29	23
6	A1	1.27	3.11	2.76	0.35	0.80	1.34	0.87	0.20	33	96	82	56	24.	14.	7.6	15	10
7	C1	1.28	3.38	2.67	0.71	0.84	0.77	0.47	0.05	29	97	76	73	10.	7.8	19	27	21
8	A1	1.28	3.18	2.62	0.56	0.86	1.20	1.08	0.19	32	97	84	56	21.	18.	11	13	11
9	E5	1.58	3.01	2.62	0.39	1.04	0.36	0.56	0.02	34	96	68	29	12.	9.3	27	27	25
10	F4	1.26	3.21	2.84	0.37	0.98	0.56	0.55	0.03	25	96	86	43	13.	9.2	19	25	21
11	E1	1.57	2.76	2.21	0.55	0.96	0.57	0.58	0.04	23	97	76	54	11.	9.7	22	29	22
12	C1	1.59	2.97	2.57	0.40	0.90	0.52	0.59	0.07	29	96	83	41	13.	9.8	21	22	21
13	B1	1.29	3.38	3.09	0.29	1.13	0.58	0.56	0.07	23	96	87	34	17.	9.3	18	30	23
14	D3	1.29	3.26	2.88	0.38	0.92	0.57	0.53	0.08	27	96	84	33	17.	8.8	20	26	22
15	B2	1.58	3.06	2.33	0.73	1.32	1.09	0.76	0.14	29	97	77	105	10.	13.	14	27	19
16	C2	1.29	3.43	2.94	0.49	1.05	0.75	0.62	0.14	27	97	87	51	15.	10.	19	28	22
17	A1	1.29	3.20	2.44	0.76	----	1.22	----	0.22	28	97	--	79	28.	---	7.9	--	--
18	--																	
19	--																	
20	D2	1.58	3.04	2.25	0.79	1.05	1.03	0.65	0.09	29	97	79	111	9.3	11.	15	24	18
21	F1	1.29	3.37	2.89	0.48	1.30	0.54	0.68	0.07	28	97	80	44	12.	11.	24	28	25
22	B1	1.58	3.17	2.61	0.56	0.90	0.81	0.59	0.11	30	96	89	68	12.	10.	17	23	19
23	A1	1.29	3.34	2.67	0.67	0.85	2.00	1.16	0.27	29	97	84	97	21	19.	7.7	12	8.9
24	E6	1.29	3.27	2.67	0.60	0.91	0.84	0.56	0.09	26	97	82	88	9.5	9.3	17	25	19
25	C1	1.58	3.04	2.20	0.84	1.01	0.93	0.61	0.10	28	98	79	75	12.	10.	18	26	20

Test #	Stov	Pot wt.	H2O wt. boil	H2O wt. simr	H2O evap boil	H2O evap simr	Fuel wt. boil	Fuel wt. simr	Char coal wt.	Strt Temp boil	Boil Temp	Strt Temp simr	Mnts to boil	Burn Rate boil	Burn Rate simr	Effc boil	Effc simr	Effc ave.
26	F1	1.59	3.02	2.50	0.52	----	0.60	----	0.08	31	98	78	53	11.	----	21	----	--
27	B1	1.59	3.08	2.59	0.49	1.06	0.77	0.52	0.09	26	98	83	58	13.	8.7	16	32	21
28	D1	1.27	3.08	2.13	0.95	----	0.89	----	0.04	28	95	--	125	7.0	---	20	--	--
29	E2	1.29	3.51	3.09	0.42	0.83	0.60	0.45	0.04	27	97	78	71	8.5	7.5	19	29	22
30	C1	1.59	3.17	2.75	0.42	0.72	0.52	0.50	0.06	26	98	82	45	12.	8.3	23	23	21
31	C1	1.58	3.13	2.67	0.46	0.87	0.61	0.53	0.07	29	97	82	51	12.	8.8	19	25	21
32	E3	1.29	3.34	3.06	0.28	0.92	0.36	0.44	0.04	27	97	79	46	7.8	7.3	27	31	28
33	C1	1.57	3.10	2.74	0.36	0.92	0.57	0.52	0.07	29	96	85	40	14.	8.7	18	27	21
34	F2	1.27	3.12	2.82	0.30	1.08	0.47	0.55	0.06	29	98	82	40	12.	9.2	21	29	24
35	B2	1.59	3.07	2.66	0.41	1.19	0.48	0.70	0.14	26	98	78	45	11.	12.	28	28	26
36	A1	1.60	3.18	2.18	1.00	----	1.81	----	0.17	28	93	--	90	20.	----	11	--	--
37	E2	1.28	3.06	2.63	0.43	0.92	0.50	0.47	0.06	30	97	84	35	14.	7.8	23	29	25
38	D2	1.29	3.29	2.99	0.30	1.03	0.55	0.58	0.08	25	98	82	40	14.	9.7	19	27	22
39	E1	1.58	3.07	2.76	0.31	1.16	0.51	0.53	0.02	29	98	77	26	20.	8.8	18	31	23
40	C2	1.30	3.19	2.83	0.36	1.04	0.61	0.58	0.10	27	97	77	43	14.	9.7	18	29	22
41	A1	1.28	3.44	3.00	0.44	1.13	1.07	1.09	0.20	32	97	85	40	27.	18.	12	16	14
42	F3	1.28	3.45	2.90	0.55	0.98	0.48	0.41	0.04	26	94	74	60	8.0	6.8	28	37	30
43	D4	1.57	3.28	3.07	0.21	0.98	0.43	0.44	0.05	27	98	80	27	16.	7.3	21	33	26
44	E2	1.59	3.08	2.79	0.29	1.30	0.52	0.56	0.06	25	97	85	32	16.	9.3	19	34	26
45	F4	1.28	3.33	3.08	0.25	1.52	0.41	0.55	0.04	27	98	86	40	10.	9.2	23	38	31
46	D3	1.29	3.32	3.06	0.26	0.94	0.36	0.45	0.05	25	97	79	33	11.	7.5	28	31	28
47	E4	1.58	3.16	2.96	0.20	1.06	0.38	0.47	0.05	28	98	80	21	18.	7.8	20	34	27
48	B2	1.29	3.24	2.88	0.36	1.07	0.51	0.53	0.13	30	97	85	48	11.	8.8	22	34	28
49	C2	1.29	3.25	3.04	0.21	1.15	0.41	----	0.08	29	98	85	24	17.	---	23	--	--
50	D2	1.58	3.08	2.46	0.62	0.88	0.66	0.51	0.11	31	98	75	82	8.0	8.5	22	29	24

Test #	Stov	Pot wt.	H2O wt. boil	H2O wt. simr	H2O evap boil	H2O evap simr	Fuel wt. boil	Fuel wt. simr	Char coal wt.	Strt Temp boil	Boil Temp	Strt Temp simr	Mnts to boil	Burn Rate boil	Burn Rate simr	Effc boil	Effc simr	Effc ave.
51	F2	1.29	3.28	3.02	0.26	1.20	0.41	0.50	0.02	27	98	82	27	15.2	8.3	22	33	27
52	E3	1.30	3.20	2.81	0.39	1.09	0.42	0.45	0.03	26	97	82	36	11.	7.5	26	34	29
53	B2	1.58	3.15	2.90	0.25	1.30	0.43	0.64	0.11	29	98	81	24	18.	11.	24	32	27
54	F1	1.28	3.23	2.79	0.44	1.31	0.41	0.47	0.06	29	98	82	45	9.1	7.8	30	42	35
55	D1	1.28	3.12	2.91	0.25	1.10	0.37	0.62	0.02	26	98	85	26	14.	10.	24	24	23
56	E5	1.58	3.08	2.46	0.62	0.79	0.74	0.54	0.07	29	88	70	60	12.	9.0	18	23	19
57	F3	1.29	3.02	2.81	0.21	1.34	0.33	0.54	0.06	26	97	80	23	14.	9.0	27	36	32
58	D4	1.29	3.15	2.90	0.25	1.16	0.68	0.25	0.07	30	98	75	24	28.	4.2	13	80	28
59	E4	1.57	3.04	2.94	0.10	1.32	0.29	0.55	0.04	27	98	79	23	13.	9.2	24	34	29
60	F4	1.29	3.11	2.70	0.41	1.02	0.41	0.48	0.07	31	98	85	49	8.4	8.0	28	32	29
61	D3	1.58	3.02	2.70	0.32	0.92	0.41	0.39	0.06	26	98	83	33	12.	6.5	25	37	29
62	E3	1.29	3.07	2.81	0.26	0.96	0.29	0.43	0.06	34	98	80	32	9.1	7.2	32	35	32
63	E2	1.29	3.21	2.95	0.26	1.43	0.37	0.57	0.06	31	98	86	23	16.	9.5	26	37	31
64	C2	1.28	3.13	2.75	0.38	0.97	0.58	0.52	0.11	24	98	80	62	9.4	8.7	21	31	24
65	E1	1.58	3.04	2.49	0.55	1.03	0.43	0.43	0.04	28	98	77	47	9.2	7.2	30	36	31
66	F2	1.29	3.08	2.84	0.24	1.15	0.32	0.52	0.06	28	98	80	26	12.	8.7	30	33	30
67	D2	1.58	3.10	2.72	0.38	0.97	0.39	0.42	0.07	29	98	78	37	11.	7.0	29	37	31
68	F1	1.29	3.14	2.86	0.28	1.10	0.32	0.35	0.06	32	98	85	28	11.	5.8	31	49	39
69	D1	1.29	3.18	2.86	0.32	0.92	0.40	0.50	0.04	29	97	79	36	11.	8.3	25	27	25
70	E5	1.59	3.24	3.01	0.23	1.24	0.39	0.66	0.03	30	98	85	23	17.	11.	21	26	24
71	F3	1.29	3.03	2.74	0.29	0.97	0.28	0.40	0.04	31	98	75	29	9.7	6.7	34	37	33
72	B2	1.59	3.06	2.76	0.30	1.07	0.45	0.56	0.10	29	97	81	32	14.	9.3	23	30	26
73	E2	1.28	3.14	2.87	0.27	1.16	0.33	0.52	0.05	30	98	83	23	14.	8.7	29	32	30
74	D3	1.59	3.04	2.59	0.45	1.07	0.40	0.49	0.07	33	98	82	46	8.7	8.2	30	33	31
75	D4	1.58	3.20	2.87	0.33	1.05	0.34	0.55	0.09	26	98	80	32	11.	9.2	36	30	30

Test #	Stov	Pot wt.	H20 wt. boil	H20 wt. simr	H20 evap boil	H20 evap simr	Fuel wt. boil	Fuel wt. simr	Char coal wt.	Strt Temp boil	Boil Temp	Strt Temp simr	Mnts to boil	Burn Rate boil	Burn Rate simr	Effc boil	Effc simr	Effc ave.
76	F4	1.29	3.10	2.73	0.37	0.97	0.38	0.41	0.05	28	98	78	37	10.	6.8	29	45	31
77	C2	1.59	2.98	2.65	0.33	1.02	0.40	0.47	0.08	29	98	82	37	11.	7.8	27	34	29
78	A1	1.28	3.40	2.96	0.44	0.86	0.88	1.09	0.19	30	95	82	45	20.	18.	15	12	13
79	E1	1.57	3.14	2.75	0.39	1.01	0.38	0.48	0.04	27	97	78	36	11.	8.0	29	31	29
80	F2	1.28	3.21	3.00	0.21	0.99	0.28	0.36	0.03	28	98	92	19	15.	6.0	30	38	34
81	D2	1.57	3.22	2.90	0.32	1.02	0.41	0.42	0.05	26	98	82	40	10.	7.0	25	37	30
82	E4	1.28	3.16	2.76	0.40	1.02	0.39	0.43	0.04	31	98	80	32	12.	7.2	28	35	30
83	B1	1.28	3.45	3.14	0.31	1.12	0.41	0.58	0.11	28	97	85	30	14.	9.7	29	30	29
84	C1	1.28	3.06	2.70	0.36	0.92	0.48	0.46	0.03	26	97	77	52	9.2	7.7	21	29	24
85	E3	1.56	3.35	2.93	0.42	1.22	0.37	0.58	0.03	27	98	76	35	11.	9.7	31	30	29
86	F2	1.28	3.04	2.64	0.40	0.94	0.32	0.33	0.01	28	97	79	40	8.0	5.5	32	40	34
87	D1	1.59	3.03	2.60	0.43	0.96	0.46	0.47	0.05	31	98	73	42	11.	7.8	24	32	26
88	E5	1.28	3.34	3.04	0.30	1.22	0.39	0.54	0.04	29	98	86	27	6.5	9.0	26	32	28
89	F4	1.28	3.41	3.20	0.21	0.99	0.26	0.41	0.03	27	98	85	19	14.	6.8	35	35	33
90	D4	1.57	3.13	2.86	0.27	1.00	0.35	0.41	0.04	27	98	80	35	10.	6.8	27	36	30
91	E4	1.28	3.36	3.03	0.33	1.04	0.43	0.46	0.02	24	97	82	36	12.	7.7	24	32	27
92	D3	1.57	3.02	2.47	0.55	0.92	0.43	0.44	0.04	32	98	79	45	9.6	7.3	29	31	29
93	F4	1.28	3.26	2.92	0.34	1.09	0.35	0.45	0.04	28	97	80	40	8.8	7.5	27	33	29
94a	E1	1.27	3.30	3.10	0.20	----	0.30	----	----	30	97	--	25	12.	---	26	--	--
94b	E4	1.27	3.21	2.90	0.31	1.21	0.38	0.55	0.04	27	97	82	35	11.	9.2	26	31	28
95	B2	1.57	3.17	2.82	0.35	1.06	0.44	0.55	0.11	27	98	86	33	13.	9.2	27	31	28
96	A1	1.28	3.20	2.86	0.34	0.83	0.81	0.98	0.15	30	89	74	50	16.	16.	12	13	12
97	C2	1.27	3.08	2.71	0.37	1.01	0.46	0.50	0.08	27	97	86	44	10.	8.3	24	31	27
98	E1	1.57	2.98	2.75	0.23	1.09	0.33	0.38	0.04	26	98	86	33	10.	6.3	26	42	33
99	F2	1.28	3.04	2.85	0.19	1.13	0.29	0.44	0.04	28	98	90	22	13.	7.3	28	36	32

Test #	Stov	Pot wt.	H20 wt. boil	H20 wt. simr	H20 evap boil	H20 evap simr	Fuel wt. boil	Fuel wt. simr	Char coal wt.	Strt Temp boil	Boil Temp	Strt Temp simr	Mnts to boil	Burn Rate boil	Burn Rate simr	Effc boil	Effc simr	Effc ave.
100	D2	1.28	3.03	2.70	0.33	0.99	0.32	0.48	0.04	28	97	83	34	9.4	8.0	31	30	29
101	B1	1.57	3.18	2.86	0.32	0.96	0.44	0.46	0.06	26	98	87	37	12.	7.7	24	31	27
102	C1	1.57	2.89	2.56	0.33	1.05	0.37	0.52	0.09	30	97	85	41	9.0	8.7	29	31	29
103	E3	1.28	3.10	2.73	0.37	1.11	0.39	0.46	0.05	27	98	84	40	9.8	7.7	28	35	31
104	F1	1.28	3.24	2.86	0.38	1.14	0.35	0.40	0.04	26	97	86	45	7.8	6.7	32	41	36
105	D1	1.28	2.97	----	----	1.21	----	0.71	0.03	27	99	89	34	---	---	--	--	30
106	E5	1.28	3.24	3.00	0.24	0.92	0.36	0.45	0.06	27	98	85	28	13.	7.5	27	31	28
107	F4	1.28	2.99	2.71	0.28	1.18	0.31	0.47	0.04	28	97	83	38	8.2	7.8	30	36	32
108	D4	1.28	3.19	----	0.40	----	0.44	----	0.06	30	96	--	55	8.0	---	29	--	--

KEY

The following is an explanation of the chart's columns.

Note that all values are in kgs.

Test #: Chronological order of the tests.

Stov: Stove code letter, for the particular stove and test variation as used in the stove design descriptions.

Pot wt.: The weight of the empty pot used in the test.

H_2O wt. boil: The weight of the water at the start of the boiling phase of the test.

H_2O wt. simr: The weight of the water at the start of the one hour simmering phase of the test.

H_2O evap boil: The amount of water evaporated away during the boiling phase of the test.

H_2O evap simr: The amount of water evaporated away during the one hour simmering stage of the test.

Fuel wt. boil: The weight of wood used during the boiling phase.

Fuel wt. simr: The weight of wood used during the simmering phase.

Charcoal wt: The weight of the charcoal remaining at the end of the test.

Effc boil: This is the PHU for the first part of the test--the boiling phase.

Effc simr: This is the PHU for the simmering phase of the test.

Effc ave.: This is the average PHU of the test as discussed in the text.

Strt Temp boil: The temperature of the water at the start of the boiling phase of the test.

Boil Temp: The temperature at which the water boils.

Strt Temp Simr: The temperature of the water at the start of the second phase of the test--the simmering phase.

Mnts to boil: The time required to bring the water to a boil.

Burn Rate boil: The fuel used during the boiling phase of the test divided by the time to bring the water to a boil. This is expressed in gms/minute.

Burn Rate simr: The fuel used during the simmering phase of the test divided by 60 minutes, to give the average rate of fuel used--expressed in gms/minute. Assuming a wood heat content of 18 KJ/Kg a burn rate of 10 gms/minute corresponds to a 3 kilowatt fire.

Analysis of the Lab Tests

Before looking in detail at the performance of the stoves tested, a number of general observations can be made on their behavior.

- Stoves without grills required repeated and frequent blowing to keep the fire going. Grills seemed to reduce this problem.
- With a very small distance between the pot and the grill there seemed to be more black smoke produced than when the distance was greater.
- In the wind, the secondary air holes seemed to allow a lot of the wind to enter the stove and disrupt the fire.
- In the wind, a lot of flames seemed to go out the door.
- Only the central portion of the stove firebox was ever used. Most of the space was unnecessary.
- A lot of flames seemed to follow the stove wall and the pot out of the stove.
- The stove with a high wall enclosing the pot seemed to allow a lot of heat to enter the pot from the side; water was observed boiling along the surface edge. This may be a problem in cooking--burning the food at the top and sides of the pot.
- For the two stoves with moveable grills, putting the grill below the door unfortunately did not change the position of the secondary air holes. In addition, because the door was fixed and bounded on all four sides, putting the grill below simply resulted in the wood entering at an angle and placed the fire at an average position between the two grill positions.

AVERAGE PHUs FOR THE STOVES TESTED*

A1 #6 10%, #8 11%, (#17 8%), #23 9%, (#36 11/%), #41 14%, #78 13%, #96 12%,

average PHU = 11.5 ± 1.87%

B1 #2 24%, #4 20%, #13 23%, #22 19%, #27 21%, #83 29%, #101 27%

average PHU = 23 ± 3.7%

B2 #15 19%, #35 26%, #48 28%, #53 27%, #72 26%, #95 28%

average PHU = 25.6 ± 3.4%

* Parentheses around a number mean that that number is not included in the average PHU calculations as there is some type of error associated with it. A slash indicates that only half of the test, boiling or simmering, was completed.

C1 #7 21%, #12 21%, #25 20%, #30 21%, (#31 21%), #33 21%, #84 24%, #102 29%

average PHU = 22.4 ± 3.2%

C2 #16 22%, #40 22%, (#49 23/%), #64 24%, #77 29%, #96 27%

average PHU = 24.8 ± 3.1%

D1 #5 23%, (#28 20/%), #55 23%, #69 25%, #87 26%, #105 30%

average PHU = 25.4 ± 2.9%

D2 (#20 18%), #38 22%, #50 24%, #67 31%, #81 30%, #100 29%

average PHU = 27.2 ± 4.0%

D3 #14 22%, #46 28%, #61 29%, #74 31%, #92 29%

average PHU = 27.8 ± 3.42%

D4 #43 26%, #58 28%, #75 30%, #90 30%, (#108 29/%)

average PHU = 28.5 ± 1.9%

E1 #1 24%, #11 22%, #39 23%, #65 31%, #79 29%, (#94 26/%), #98 33%

average PHU = 27 ± 4.6%

E2 #29 22%, #37 25%, #44 26%, #63 31%, #73 30%

average PHU = 26.8 ± 3.7%

E3 #32 28%, #52 29%, #62 32%, #85 29%, #103 31%

average PHU = 29.8 ± 1.6%

E4 #3 24%, #47 27%, #59 29%, #82 30%, #91 27%, #94 28%

average PHU = 27.5 ± 2.1%

E5 #9 25%, #56 19%, #70 24%, #88 28%, #106 28%

average PHU = 24.8 ± 3.7%

E6 #24 19%--one test only

F1 (#21 25%), (#26 21/%), #54 35%, #68 39%, #104 36%

average PHU = 36.7 ± 2.1%

F2 #34 24%, #51 27%, #66 30%, #80 34%, #86 34%, #99 32%

average PHU = 30.2 ± 4.0%

F3 #42 30%, #57 32%, #71 33%

average PHU = 31.7 ± 1.5%

F4 #10 21%, #45 31%, #60 29%, #76 31%, #89 33%, #107 32%, #93 29%

average PHU = 29.4 ± 4.0%

Looking at the data above we see a definite improvement in efficiency for each stove, and variation from the first tests to the last. This is as expected due to the problems of methodology (wind, wood moisture content, etc.) already cited. Qualitatively, one sees rough stability in the calculated efficiency after tests 40 to 60. Linear regressions--test number versus PHU--can be done on the above data to determine the strength of the variation with time, and thus understand the impact of the poorly controlled variables such as wind, wood moisture content, and operator learning time. The results are given in the table which follows.

The linear regression was done with the test number as the X variable, the PHU as the Y variable, and only the tests within a particular stove variation included. The results are displayed below with Y being the y-intercept for the calculated line, M the slope of this line, and R the correlation coefficient.

In the table on the following page, variations F1 and F3 are not included due to insufficient data. (Lack of data is generally a problem in the calculations there.)

It is interesting to note the strong correlations and slopes with test number. It is also important to note in test variations B1, B2, C1, E4, and F4, that removal of a few data at the beginning or end of the test sequence all but eliminated the trend in the data. In other cases, such as D1, the trend remained strong throughout the sequence of tests.

Thus, because of the limited quantity of data available and the strong trends with test number, we will not continue with an extensive analysis of this data, but will wait until further data is available. However, some tentative conclusions can be extracted from the data.

First, the stoves that were completely closed except for the door showed higher efficiency, as seen in every case in which B2 was compared to B1, C2 to C1, and D4 to D1. The data consistently show that the closed stoves had more charcoal remaining at the end of the test. This can be interpreted as a combination of poorer combustion and the use of too large a value, 29,000, for the calorific value of charcoal. In support of this, it was found in performing the tests that for closed stoves it was necessary to repeatedly blow on the fire to keep it going. Grills are preferred for this reason.

TREND ANALYSIS OF DATA

Stove	Y	M	R
A1--all data	10.3	.028	.56
B1--all data	20.7	.072	.77
#2,4,13,22,27	22.6	-.09	-.48
B2--all data	21.1	.087	.72
#35,48,53,72,95	26.0	.016	.39
C1--all data	19.2	.078	.90
#7,12,25,30,33	20.9	-.007	-.18
C2--all data	19.9	.083	.84
D1--all data	21.4	.063	.83
D2--all data	18.7	.125	.78
D3--all data	22.0	.099	.86
D4--all data	22.6	.089	.95
E1--all data	21.8	.107	.89
E2--all data	17.4	.192	.95
E3--all data	27.8	.030	.51
E4--all data	24.8	.043	.73
#47,59,82,91,94	27.7	.006	.10
E5--all data	21.9	.044	.44
F2--all data	19.6	.152	.91
F4--#45,60,76,89,93,107	29.1	.022	.31

Note: all data refers to all PHU data in the previous table, save those in parentheses.

"#" refers to the test numbers included in the calculation.

Second, in determining the effect of grill height on efficiency, with or without secondary air, one finds by comparing tests E1 to E2, E3 to E4, F1 to F2, and F3 to F4 that in every case, lowering the grill lowered the efficiency. At the same time, however, lowering the grill qualitatively reduced the amount of black smoke from the stove. Perhaps lowering the grill reduced the radiant exchange more than it improved the combustion gains.

Third, in examining the effect of secondary air on stove performance we find mixed results. In stoves D and E (compare tests D1 to D3, E1 to E3, and E2 to E4), closing the secondary air holes improved the efficiency. One might interpret this as reducing the amount of cold air which enters and cools the pot while aiding combustion only minimally. However, closing the secondary air holes reduced the efficiency in both cases in stove F (compare F1 to F3 and F2 to F4). This mixed behavior is not understood.

Finally, in examining the effect of the wall height on stove efficiency we see by comparing tests E1 to F1, E2 to F2, E3 to F3, and E4 to F4, that stove F performed better than stove E in every case. This is not unexpected. The higher wall reduces the heat loss from the pot and increases the effective heat transfer area.

Conclusions and Future Work

In the detailed lab tests presented here we have found high to very high PHUs for all stoves tested. In particular, Stove F had PHUs above 35%. Methodological problems, now observed, can be brought under greater control.

Further testing will be done with these stoves to develop a better statistical base and allow detailed quantitative analysis of their relative performance. Additional variations will also be tested.

Variations that appear promising include:

- Cylindrical insert. A cylindrical piece of fired clay could be set in the center of the stove body to act as a combustion chamber. This may have advantages in providing, effectively, a double wall; in preheating the primary and secondary air; and in better focusing the flames on the bottom of the pot.

- Roughened stove walls. As the fired clay can be molded as desired before firing, the inner surface of the stove close to the pot can be roughened to increase the turbulence and thus perhaps improve the heat transfer to the pot. Alternatively, semi-spiral ridges could be formed into the inner surface of the stove wall to increase the retention time of the hot gases and, thus, perhaps improve the heat transfer.

Additional results will be forthcoming shortly.

II. THE ECONOMICS OF IMPROVED STOVES

Introduction and Methodology

A series of simple calculations following procedures of Thuesen et. al. and French were done to get an idea of the economic value of improved stoves to the family owning them under various situations, and to estimate the economic sensitivity of the stoves to various parameters. Calculations were based on the Net Present Value (NPV) of the stove, defined as:

$$NPV = EDA - CB \qquad \text{(Equation 1)}$$

where multiplication is implicit for two adjacent variables, i.e. **CB = C x B**, and the variables are defined as:

E is the wood economy realized by the stove, i.e. the reduction in wood use from a traditional stove. If a stove used only 60% of the amount of wood that would have been used by the same family with a traditional three stone fire, then $E = 0.40$.

D is the daily cost of wood for the family. In major towns such as Ouagadougou, **D** can be 200 CFA/day and more (US$1.00 = 350 CFA); in the countryside, where women and children collect the wood, **D** is going to be very small as far as the cash economy is concerned.

A is present worth of an annuity factor [or the "equal-payment-series present worth factor" (Thuesen)] and is given by:

$$A = \frac{(1+r)^n - 1}{r(1+r)^n} \qquad \text{(Equation 2)}$$

(Note: in equation **(2) r** should be adjusted to equal the daily interest rate, which is consistent with the period of **n)**.

where **r** is the specified interest rate given by:

$$r = z((1+i)^{1/z} - 1) \qquad \text{(Equation 3)}$$

n is the total number of compounding periods, **i** is the effective annual interest rate, and **z** is the number of compounding periods per year. As wood will be assumed to be purchased daily, $z = 365$ and $n = 365$ times the number of years considered.

C is the initial cost of the stove

B is the "present worth factor" (discount factor) for purchasing stoves. The factor **B** will be determined by the lifetime of the stove. For stoves lasting one year or more their future costs are discounted to the present by the simple formula:

$$B = 1/(1+i)^n \qquad \text{(Equation 4)}$$

and summed. For stoves lasting less than one year, B will be determined by a form similar to equation (2), with appropriately adjusted values for **r**, **n**, **i**, and **z**. Though it has little effect on A due to daily compounding, it is important to note that for **B**, equation **(2)** assumes the first payment is at the end rather than the beginning of each period. In calculating **B**, the last compounding period (i.e. one period) must be subtracted from n in equation **(2)**, and the value "1.0" be added to B to represent the initial cost at the start of the first period.

Before actually beginning the calculations, it is important to make three additional points.

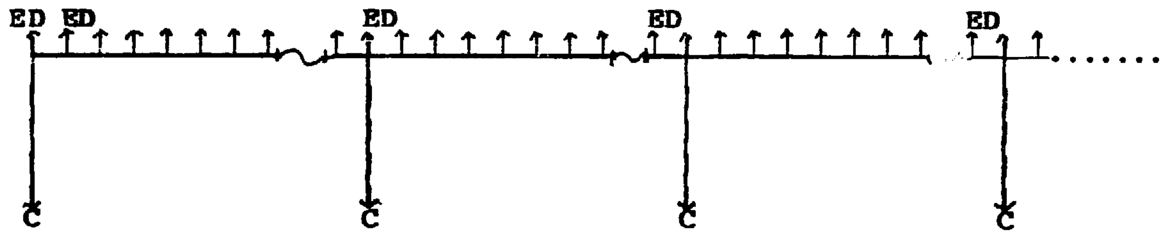
First, as noted by David French, the real investor discount rate (or interest rate) i in equation **(3)** is considerably higher for poor people in third world countries than it is for people in the mainstream world market economy. The causes, among others, are their short term view (through the next harvest), their narrow margins of survival (risks must be weighed carefully), and a simple lack of cash to invest. The result is a very high discount rate. In his work, French cites World Bank data for commercial interest rates for agricultural credit ranging as high as 192%, with most countries falling in the "20 to 66% range". He chose a value of 50% for Chad; we will assume that value here as a starting point.

Second, as the supplies recede from their point of use and generally decrease in size, the real cost of wood will increase with respect to other goods. Wardel and Palmieri estimate this average world increase since 1970 to be 1.5 to 2.0% per year. Though the increase is likely due in large part to oil price increases, the Tata Energy Research Institute cites fuel wood price increases of 300% in two years in Kathmandu. Though significant, for the sake of simplicity we will ignore this factor here. Except in the most extreme circumstances this is justifiable due to the short time spans and large effective discount rates to be considered, and to the fact that these calculations are crude to begin with; they are for illustrative purposes only.

Third, these calculations concern only the net financial benefits to individuals who buy the stoves. The societal costs of deforestation, the impact on employment in the wood gathering and transportation sectors versus the stove building and maintenance sector, etc., will not in any way be considered here.

The form of the calculation is then: the value of the wood saved daily in the improved stove compared to a traditional three stone fire, and the cost of the stoves periodically purchased as determined by their average lifetime, all discounted with the appropriate factors to the present and summed. This takes the diagrammatic form given on the next page. The daily savings in expenses for wood, **ED**, are shown by the individual little arrows. The periodic cost of buying a new stove is shown by the large arrows. Factors A and B in equation (1) do all the necessary discounting and summing automatically.

SAVINGS



EXPENSES

The daily savings in expenses for wood, **ED**, are shown by the individual little arrows. The periodic cost of buying a new stove is shown by the large arrow. Factors A and B in equation (1) do all the necessary discounting and summing automatically.

Calculations

For all the calculations that follow we will consider a period of four years--chosen simply for convenience.

To begin, we calculate the factors A and B for different annual interest rates and stove lifetimes and list them in the table which follows.

In the table one can quickly see at 0% interest at the Net Present Value the cost each day for the following 1,431 days over four years. Similarly, for a three month stove lifetime one sees the cost of all 16 stoves over four years.

As the annual interest increases, one's "time horizon" shortens so that at 200% interest, one can "see" at the present the cost of wood for only 329 of the following 1,431 days. Similarly, for a stove with a three month lifetime, one "sees" the cost of only 4.1 of the 16 stoves that will actually be purchased. On the other hand, for a stove with a four year lifetime, as the entire cost is paid in the first day, its Net Present Value is the same no matter what the interest rate. Thus, if we were to choose between a stove with a four year lifetime costing 10,000 CFA, or 16 stoves with just three month lifetimes costing 1,000 CFA each, all other things being equal, with any effective interest rate over 32% it would make more sense to invest in the stoves with shorter lifetimes.

i	A	B 3 month*	B 6 month*	B 1 year*	B 2 year*	B 4 year*
0	1,431	16.00	8.00	4.00	2.00	1.00
10	1,215	13.46	6.81	3,49	1.83	1.00
20	1,037	11.62	5.94	3.11	1.70	1.00
30	905	10.24	5.29	2.82	1.60	1/00
40	803	9.17	4.78	2.60	1.51	1.00
50	724	8.32	4.37	2.41	1.44	1.00
60	659	7.64	4.05	2.26	1.39	1.00
70	606	7.08	3.78	2.14	1.35	1.00
80	563	6.62	3.55	2.04	1.31	1.00
90	526	6.23	3.36	1.95	1.28	1.00
100	492	5.90	3.20	1.88	1.25	1.00
120	442	5.35	2.94	1.76	1.21	1.00
140	404	4.93	2.74	1.66	1.17	1.00
160	374	4.60	2.58	1.59	1.15	1.00
180	349	4.33	2.44	1.53	1.13	1.00
200	329	4.11	2.25	1.48	1.11	1.00

*stove lifetime

In Figure 1 below, the Net Present Value (NPV) for various stoves and effective interest rates is calculated. These curves were calculated from Equation (1) for a stove with a one year lifetime. The other parameters used in this calculation were:

Curve I: E = 0.5; D = 100 CFA/day; C = 1,000 CFA

Curve II: E = 0.5; D = 100 CFA/day; C = 5,000 CFA

Curve III: E = 0.3; D = 100 CFA/day; C = 5,000 CFA

Curve IV: E = 0.3; D = 50 CFA/day; C = 5,000 CFA

Curve V: E = 0.3; D = 500 CFA/day; C = 5,000 CFA; lifetime of two years

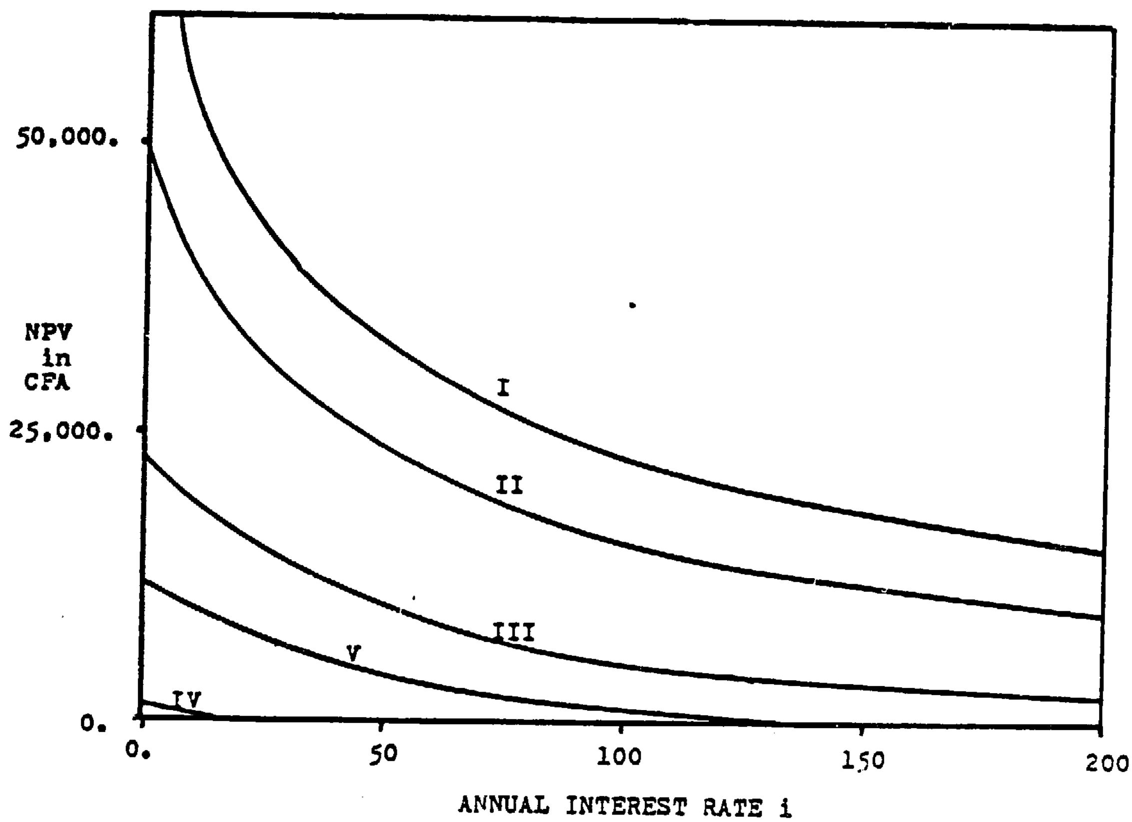


Figure 1

Net Present Value in CFA versus different annual interest rates. Parameters corresponding to the curves labeled I-IV are given above (Note the order I, II, III, V, IV due to the improved lifetime of Curve V's stove.)

Now the question is which of the situations shown in Figure 1 we are likely to be operating under. First, though many different sources claim wood economies of 50% and more for massive stoves (i.e. two hole cement stoves with chimneys), this has rarely been substantiated and never over the life of the stove. An average 30% wood economy over the lifetime of the stove is optimistic for massive stoves. Second, the daily cost of wood will be as high as 100 CFA/day or more only in the largest cities far removed from sources of fuel. In the countryside daily costs will generally be less than 50 CFA. Third, stove costs are typically 5,000 CFA for cement stoves with lifetimes usually quoted as two years. Thus we find that high investment stoves (5,000 CFA for cement stoves) will be at best marginally economic for regions where daily wood costs are 50 CFA or less. Of course, their economics improve rapidly where the daily wood cost is higher. Clearly, however, cheaper and more efficient models will be needed if they are to succeed in the countryside.

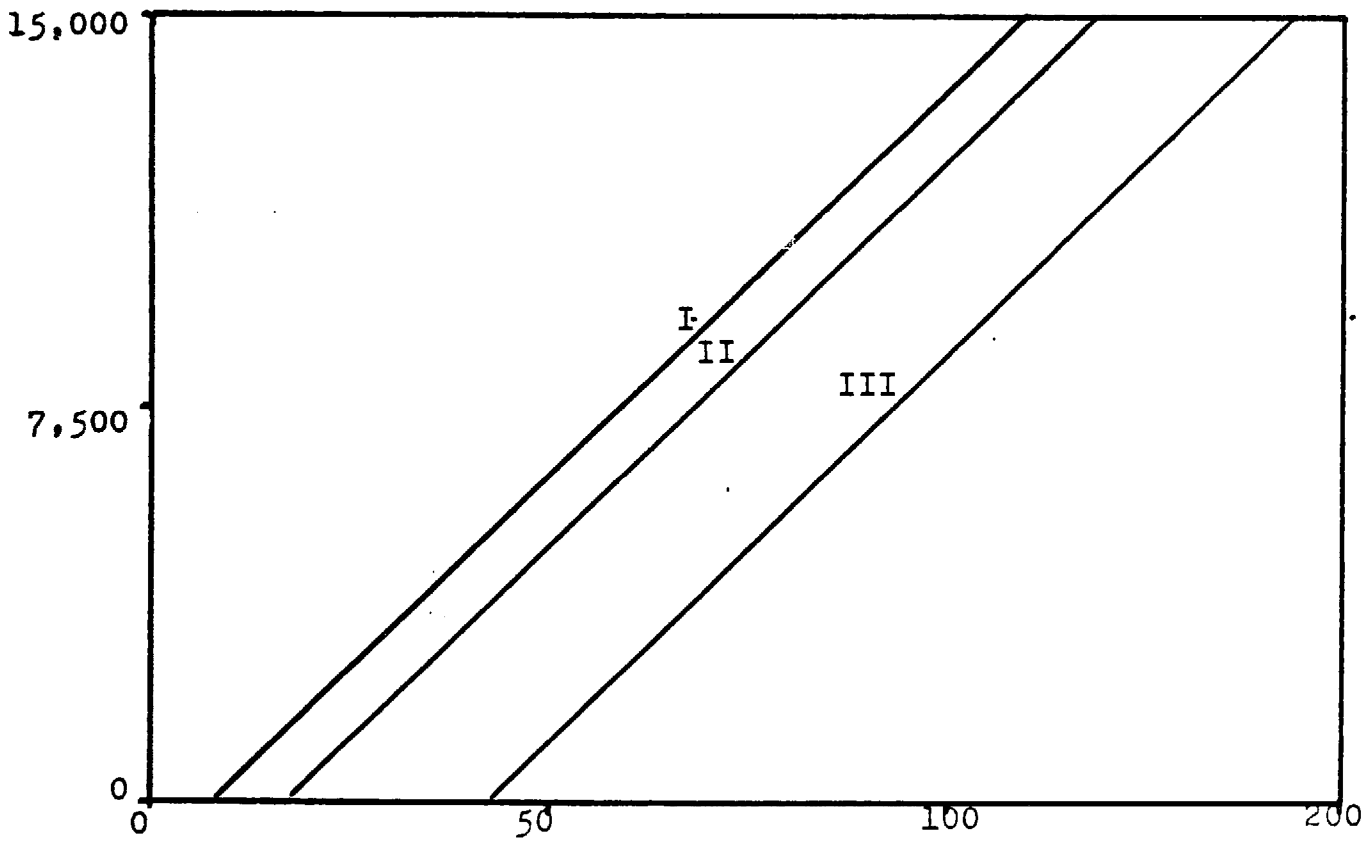


Figure 2

Net Present Value for stoves in regions with differing wood costs

The dramatic effect of the daily wood cost on the economics of stoves can be seen in Figure 2. The curves all used a lifetime of two years, 100% interest rate and wood economy of 30%. Beyond that, the following values were used:

I: Stove Cost C = 1,000 CFA

II: Stove Cost C = 2,000 CFA

III: Stove Cost C = 5,000 CFA

Perhaps a better understanding of the economics here as seen by a potential user can be obtained by looking at the ratio of the NPV of the stove to the initial investment. Thus, as seen in Figure 3 below, in a region where the daily wood cost is 100 CFA, a stove costing 5,000 CFA (Curve III) has a NPV of only 1.71 times the initial investment, while a stove with an initial cost of 1,000 CFA has a NPV 13.5 times as large as the initial investment--clearly the cheaper stove can be seen as a dramatically more desirable investment.

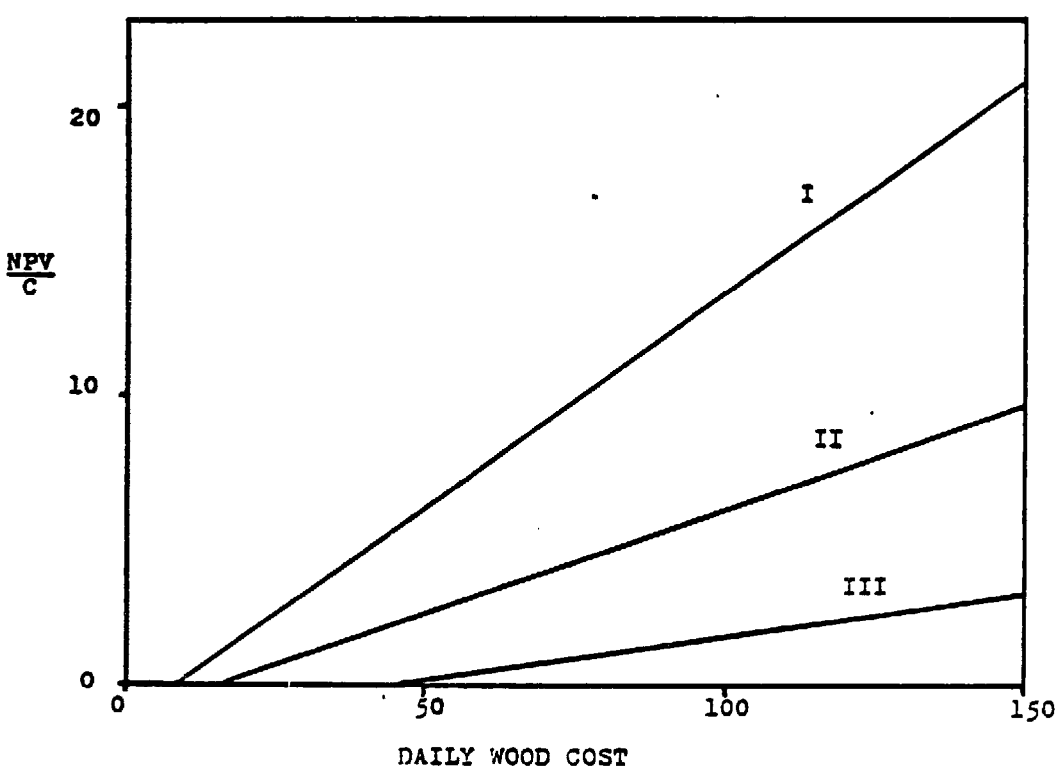


Figure 3

Net Present Value divided by Stove Cost, NPV/C, versus the daily wood cost. Parameters for curves are the same as Figure 2--two year lifetime, 100% interest rates, wood economy of 30%. In Curve I, C = 1,000CFA; II, C = 2,000 CFA; and III, C = 5,000 CFA.

Using these same ideas we can develop a chart showing the sensitivity of the stove economics to different parameters. This will not be a calculation of Net Present Values. Rather, shown below is the ratio of total costs for providing the service--cooking food--by different means. Our basis for comparison will be the traditional three stone fire. Total costs for it are the costs of daily purchases of wood, given by the factor **DA** in equation **(1)**. The alternative cooking system, the improved stove, has a total cost of daily purchases of wood, given by **(1-E)DA**, and purchases of stoves, given by **CB**. Thus we find for the ratio of total costs:

$$R = (1-E) + CB/DA \qquad \text{(Equation 5)}$$

In calculating the curves from Equation **(5)**, we will plot R versus the percentage change in a specified parameter. It is important to note that the percentage variation in wood economy is relative to an open fire. Thus for an open fire with PHU of 10%, E = 0.5 implies a PHU of 20%. For a 200% reduction in E we then find a PHU of 12.5%, giving an E of 0.20. For a 200% increase in E we find a PHU of 40%, giving an E of 0.75.

Equation **(5)** is plotted in Figure 4 on the following page with starting values (baseline at 0%) of:

interest, i = 50% (**A** = 724)

daily wood cost, D = 50 CFA/day

wood economy, E = 0.50

initial cost, C = 1,000 CFA

lifetime = 1 year (**B** = 2.407)

From Figure 4 we see that the most sensitive determinant of the ratio of cooking costs with a stove to an open fire is the stove efficiency **E**. This is followed by the daily cost of wood D and lifetime at low values, and initial cost of the stove C at high values. The effective interest rate is a key factor in determining the starting position, but is not considered beyond that: of course, we have already seen in Figure 1 that the interest rate has a strong effect on the value of the **NPV** itself. In the diagram which follows, changing the interest rate has little effect, as both **A** and B change by nearly proportional amounts, leaving their ratio B/A almost the same.

The following stove corresponds crudely to a fired clay stove (with the question of lifetime as yet totally unanswered), and we see that even with large individual variations in parameters the stove remains cheaper to use than a traditional three stone fire (**R** is less than one).

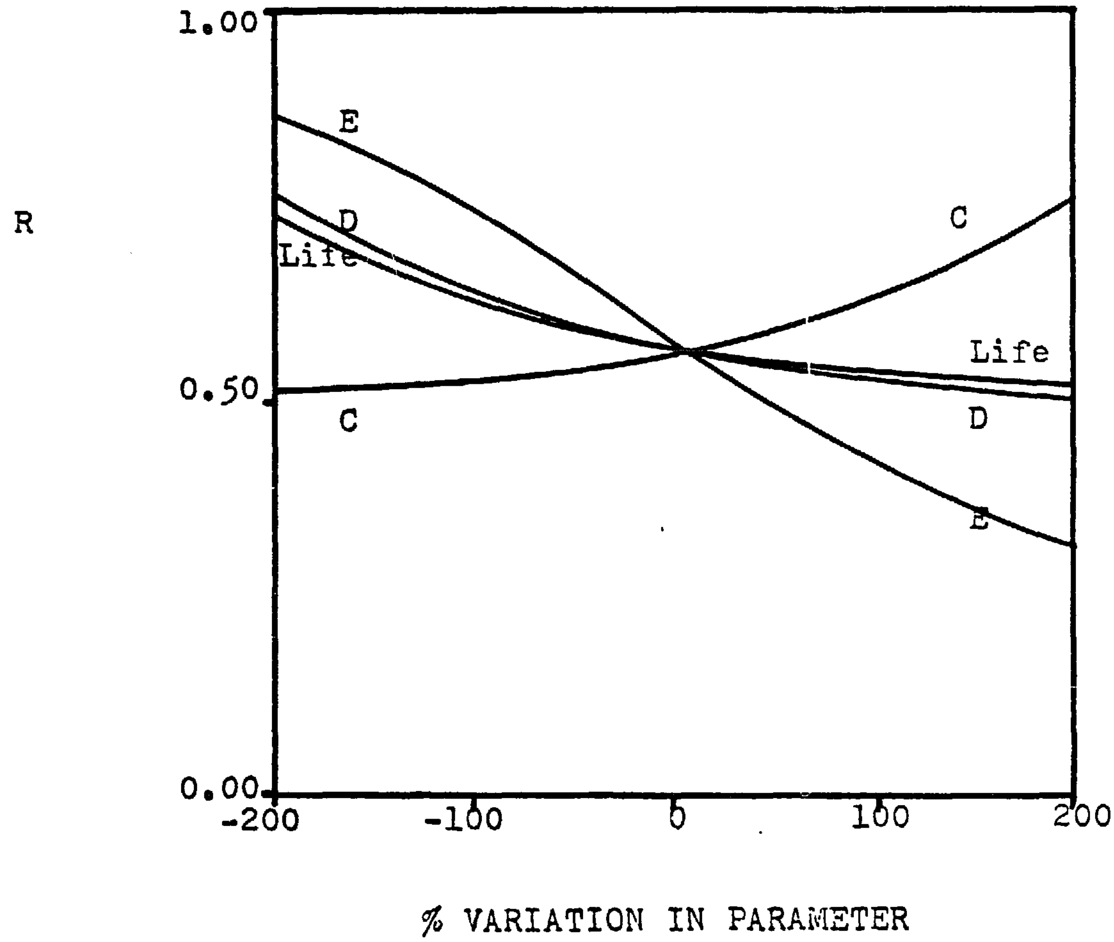


Figure 4

Ratio of stove costs to open fire costs, versus the percentage variation in particular parameters. Costs include daily purchases of wood and stove purchases over a four year timespan, and are discounted to the present using the factors **A** or **B** respectively. Initial conditions are i = 50%, **D** = 50 CFA/day, **E** = 0.5, **C** = 1,000 CFA, and lifetime = 1 year.

For comparison, we can do a similar calculation for massive stoves. Starting with the parameters:

interest, **i** = 50% (**A** = 724)

daily wood cost, **D** = 50 CFA/day

wood economy, **E** = 0.33 (PHU = 15%, if three stone fire = 10%)

initial cost = 5,000 CFA

lifetime = two years (**B** = 1.444)

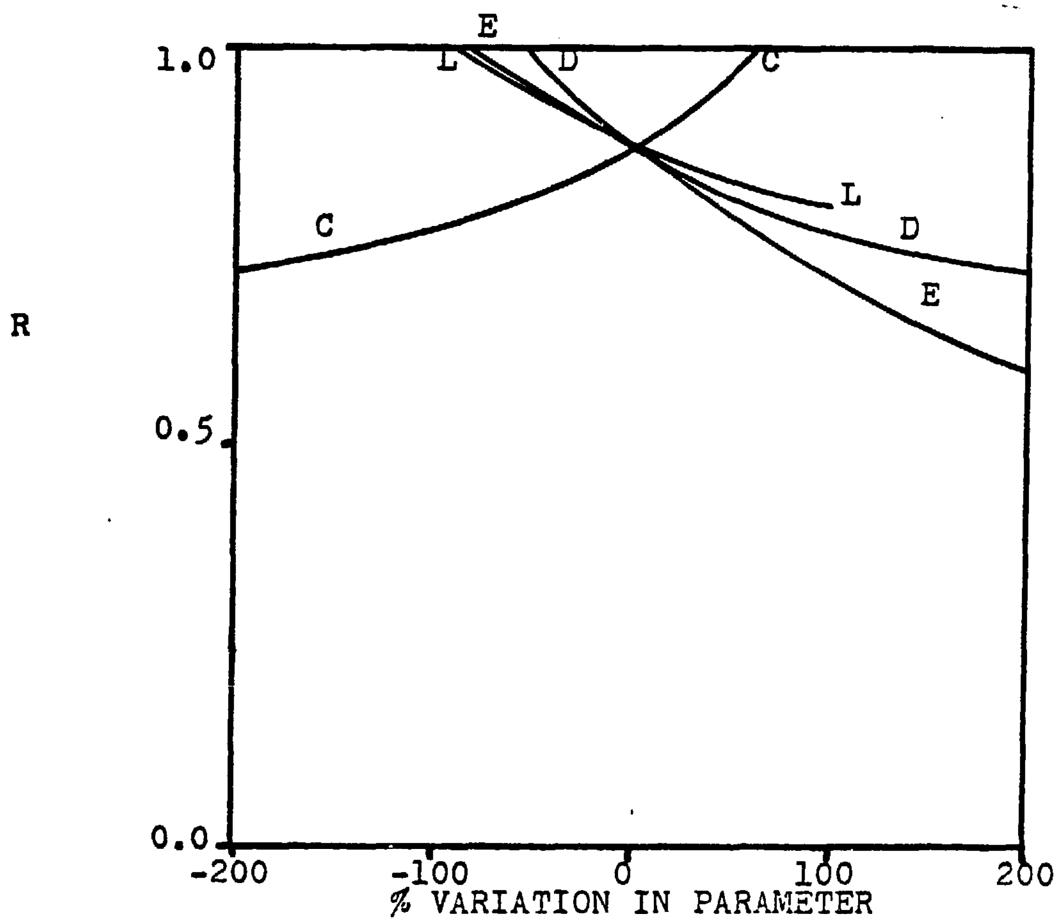


Figure 5

Ratio of massive stove costs to open fire costs, versus the percentage variation in selected parameters. L is the lifetime, with a starting point of two years. As the calculation only covers a four year timespan, L stops at 100% increase. Other initial conditions are D = 50 CFA/day, E = 0.33, C = 5,000 CFA and i = 50%.

First of all, we note in Figure 5 that given the initial conditions the stove shows only a 13% reduction in total costs compared to a traditional three stone fire. Second, we note that rather small changes for the worse quickly reduce and can even eliminate the stove's advantage over the traditional three stone fire. A decrease in lifetime from two years to one year, a decrease in wood economy from 33% to 20%, a decrease in daily wood cost from 50 CFA to 35 CFA, or an increase in stove cost from 5,000 to 7,500 CFA all individually eliminate the stove's advantage. Any of these separately are likely to happen. Further, as their effects are additive, the economics of this stove are that much more precarious.

Certainly, massive stoves can and have demonstrated a clear wood savings and a definite economic advantage in a number of cases. The above calculation, for example, began with a daily wood cost of 50 CFA. In many areas the wood cost for a family is higher than that, and in these areas the economic advantage of a stove will be much larger, and the sensitivity of the stove's economics to changes in efficiency, lifetime, initial cost, etc., will be accordingly reduced. The importance of the above calculation is not to discount the value of massive stoves, but rather to show their sensitivity to design parameters and the need for careful design, high quality construction, and long term follow-up. Secondly, it is hoped that this exercise will provide a focus for data collection by workers in the field so that more precise and more detailed analyses can be done by economists in the future. Finally, it is hoped that this exercise will stimulate further debate, particularly on how to approach the question of auto-diffusion.

A further caution about misuse of the above calculation is that it is only a financial calculation and in no way includes the greater societal advantages of reducing wood consumption and deforestation. Currently, large sums are being spent in West Africa on reforestation. A "typical plantation" will cost US$ 700 to 800/ha to plant, have upkeep costs of roughly 10% of that per year, and will produce 5 to 10 m^3/ha/year of wood after perhaps five years. Thus, over 20 years at a present cost (assuming commercial interest rates of 15%/year) of roughly $1,100 to 1,300, some 75 to 150 m^3 of firewood will be produced. Alternatively, a family of 10 will use about 7 to 8 m^3/year of firewood. An improved massive stove will save roughly 30% of this or 2 to 2.5 m^3/year. Thus, if five years after the plantation is started, 3 to 4 families are provided stoves for the following 15 years, the same result is achieved--that is, a reduction of 5 to 10 m^3/year of wood cut from natural forests. The present value of these stoves (assuming an initial cost of 5,000 CFA = $14, replacement every two years, and the same 15% interest rate) is $75 to $100, which is 6 to 7% of the cost of providing the same service by planting fuelwood plantations.

The preceding calculations indicate that stoves can economicly succeed under certain conditions. They also point out the economic sensitivity of stoves under other conditions. Considerably more work must be done--technical, economic, and social--to realize the tremendous potential that stoves promise. It is hoped that this report provides a focus for some of that work.

III. STEADY STATE HEAT LOSS IN MASSIVE STOVES

In this section we will take a brief and extremely idealized, simplistic look at the steady state heat loss from a massive stove. Though the analysis that follows is unquestionably inadequate, it does cast some light on the behavior of massive stoves.

It is widely recognized that the more massive a stove, the longer it takes to heat up, and that this can be a severe penalty where cooking times are short. What the analysis below shows is that even in the steady state, under special conditions there may be greater heat loss from the stove if the thickness of the walls is increased. Even where such special conditions do not exist, the reduction in heat loss by making a stove more massive will not likely be worth the cost in terms of longer warm-up times.

A standard student exercise is calculating the heat loss from a wire with varying thicknesses of insulation. It is found that under appropriate conditions one can increase heat loss by increasing the thickness of the insulation. Thus electrical wires can be better insulated electrically at the same time that more effective cooling is provided. The simple exercise presented here is an extension of this to the case of a sphere, representing here a massive stove.

To begin, we consider the steady state heat loss from a spherical shell in space with a constant heat source at its center, inner radii and temperature of **r1** and **T1**, and external radii and temperature of **r2** and **T2**. The conductivity of the shell is k and the outer surface heat loss coefficient is h. This is depicted in Figure 6. When comparing this idealized case to that of a massive stove one must note that adding to the thickness of a wall adds also to the top, side, and bottom surfaces. We have here simply rounded off the edges of the stove to obtain a sphere.

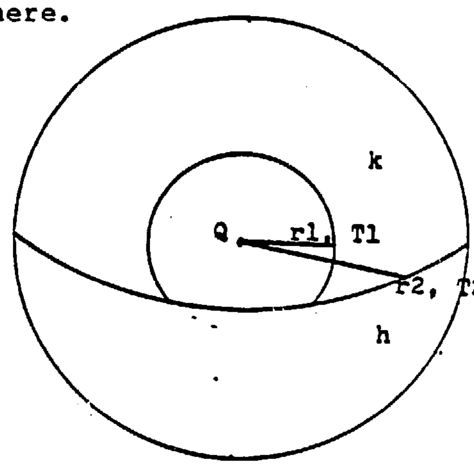


Figure 6

Spherical shell of inner radii and temperature **r1**, **T1**, and external radii and temperature **r2**, **T2**. Shell has conductivity k and surface heat loss coefficient h. At the center is a constant heat source **Q**.

As we have a completely symmetric steady state situation, the heat conduction equation can be written (Eckert and Drake):

$$\frac{d^2(rt)}{dr^2} = 0 \qquad \text{(Equation 6)}$$

with general solutions for the temperature distribution t within its shell of:

$$t = A + B/r \qquad \text{(Equation 7)}$$

Boundary conditions give:

$$A = \frac{T1r1 - T2r2}{(r1 - r2)} \text{ and } B = \frac{(T1 - T2)}{(1/r1 - 1/r2)} \qquad \text{(Equation 8)}$$

Using the Fourier conduction law:

$$Q = -k(4\pi r^2)\frac{dt}{dr} \qquad \text{(Equation 9)}$$

we find:

$$Q = \frac{T1 - T2}{\frac{r2 - r1}{4\pi kr1r2}} \qquad \text{(Equation 10)}$$

The term in the denominator of equation 10 is the thermal resistance to heat loss by the shell. As can be seen in Figure 7 on the next page, its resistance increases slowly with r2--more slowly the larger r2 becomes.

By standard procedures we can include a lumped thermal resistance for heat loss by radiation and convection from the outer surface of the shell (Eckert and Drake) and find:

$$Q = \frac{T2 - T1}{\frac{1}{4\pi r^2 h} + \frac{r2 - r1}{4\pi kr1r2}} \text{ where } r_2^2 \text{ is } (r2)^2 \qquad \text{(Equation 11)}$$

The heat loss is a maximum when the denominator is a minimum. Keeping r1 fixed and taking the derivative of the denominator alone with respect to r2, we find the maximum heat loss occurs (setting the derivative to zero) for:

$$r2 = \frac{2k}{h} \qquad \text{(Equation 12)}$$

This can be easily evaluated. As above we estimate that k=1.0 W/mC. The surface heat loss coefficient, h, is difficult to evaluate and highly sensitive to the effects of wind, etc. From Meinel and Meinel we find values of h ranging from below 5 W/m^2C in still air to over

15 W/m^2C in a 3 m/s wind. Obviously, these dramatically affect one's estimate of the critical radius, 2k/h, at which maximum heat loss occurs. It is more important to note that thicker walls, under the above conditions, do not significantly reduce the heat loss.

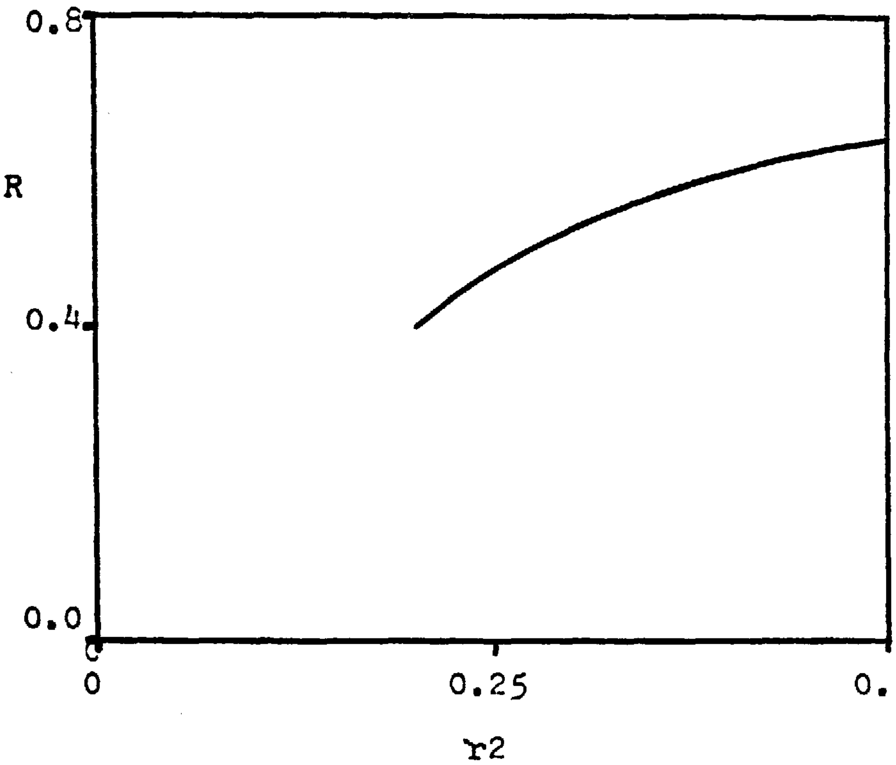


Figure 7

Resistance R to heat loss by the spherical shell (the denominator of equation (10) versus r2. The inner radii, r1, is assumed to be 0.1 m and the thermal conductivity, k, is assumed to be 1.0 W/mC, where W is watts, m is meters, and C is degrees centigrade. By comparison, clay has k = 1.2 W/mC, sand has k = 0.4 W/mC, and cement has k = 0.8-1.4 W/mC.

In Figure 8, the heat loss from the wall, Q(W), is plotted versus the thickness of the wall, here given by r2-r1. The parameters used in making this calculation were: r1 = 0.1 m; T2-T1 = 500 C; k = 1.0 W/mC. For Curve I a 3 m/s wind was assumed, giving h = 15 W/m^2C; while for Curve II still air was assumed, giving h = 5 W/m^2C.

In Figure 8, both types of behavior discussed above can be seen. Curve I has reduced heat loss for all values plotted. This is expected, as in this case the critical radius 2k/h is just 13.3 cm and we began with r1 = 10 cm. On the other hand, Curve II shows an increase in heat loss with wall thickness up to a thickness of about 30 cm (r2 = 40 cm). In this case, the stove is in still air with a surface heat loss coefficient of h = 5 W/m^2C, and we do in fact find from equation (12) that the critical radius is 0.4 m. In both these cases it is important to note that increasing the wall thickness does not greatly reduce the rate of heat loss.

Though this calculation is certainly too simplistic and far from complete, it does suggest that thicker stove walls do not significantly reduce heat loss. More detailed analysis is in progress.

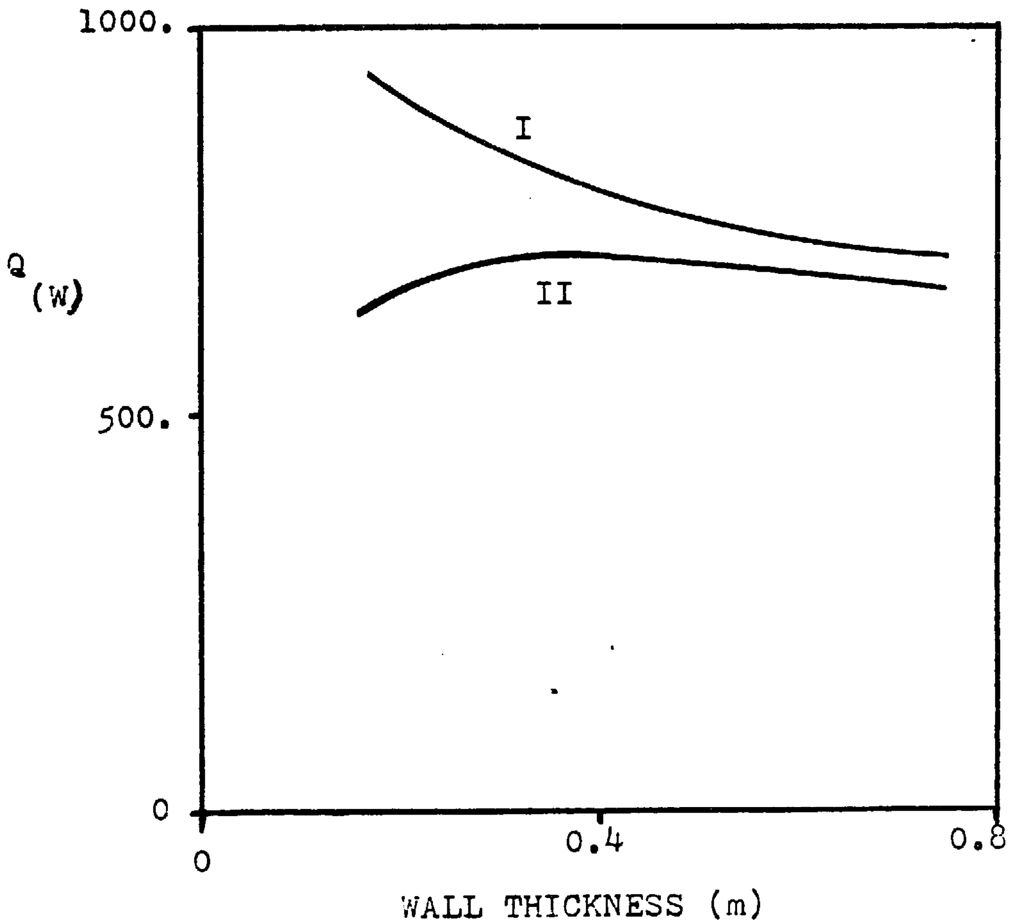


Figure 8

Heat loss versus wall thickness

REFERENCES

Brownlee. Statistical Theory and Methodology in Science and Engineering, John Wiley and Sons, 1965.

De Lepeleire, Prasad, Verhaart, and Visser. A Woodstove Compendium. Prepared for the UN Conference on New and Renewable Sources of Energy, Nairobi, 1981. Available from Eindhoven University of Technology, Postbus 513, 5600 MB Eindhoven, The Netherlands.

De Lepeleire. Report of the working group meeting on a woodstove field test standard, Marseille, 12, 13, 14 May 1982.

Downey. Stove Testing Procedures (draft manuel, also available in French). VITA, 1815 N. Lynn St., Arlington, Va 22209, 1981.

Eckert and Drake. Analysis of Heat and Mass Transfer. McGraw-Hill, Inc., 1972.

French. "The Economics of Renewable Energy Systems for Developing Countries." 4417 Q Street, N.W., Washington, D.C. 20007, January 1979.

Joseph and Trussell. "Report on Advisory Visit to the VITA Wood Stove Project in Upper Volta, 16 February to 2 March 1981." ITDG, 9 King Street, London WC2E 8HN, U.K.

Joseph and Shanahan. "Designing a Test Procedure for Domestic Wood Burning Stoves." ITDG, 1980.

Joseph and Shanahan. "Laboratory and Field Testing of Monolithic Mud Stoves." ITDG, 1981.

Joseph. "Stove Testing." ITDG, 1979.

Meinel and Meinel. "Applied Solar Energy." Addison Wesley, 1976.

Prasad, et. al. "Some Performance Tests on Open Fires and the Family Cooker." The Woodburning Stove Group, Department of Applied Physics and Mechanical Engineering, Technical University of Eindhoven, Postbus 513, 5600 MB Eindhoven, The Netherlands.

Prasad, et. al. "A Study on the Performance of Two Metal Stoves." Eindhoven, February 1981.

Prasad, et. al. "Some Studies on Open Fires, Shielded Fires, and Heavy Stoves." Eindhoven, October 1981.

Tata Energy Research Institute. "Cookstove Handbook." Bombay House, 24 Homi Mody Street, Bombay 400-023, June 1982.

Thuesen, Fabrycky, and Thuesen. Engineering Economy. Prentice-Hall, 1977.

VITA. "Stove Testing Procedures." VITA News, October 1981.

Wardle and Palmieri. "What does fuelwood really cost?" Unasylva, Vol. 33, no. 131, 1981, p. 20.

Wood, Field Report B-2, "More Stove Tests" and "Metal Stove vs. 3 Stones." VITA, September 1981.

Wood. Field Report B-3: "Ceramic Portable Stove." VITA, October 1981.

Wood. Field Report B-4: "Woodstove Testing: Evaluation of Local Materials." VITA, October 1981.

Wood. "The Hazards of Testing Improved Wood-Burning Stoves." BOSTID Developments, Vol. 1, no. 4, December 1981.

Wood. "Laboratory and Field Testing of Improved Woodstoves in Upper Volta." Report to BOSTID/NAS. VITA, June 1981.