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STATE-OF-THE-ART REVIEW
DESIGNING RURAL COOK STOVES

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1. Introduction

The cooking activity in rural households accounts for about 3/4 of the total domestic energy use. Household consumption is the dominant energy demand except in villages with highly mechanized agriculture or considerable industrial activity. The experimental thermal efficiency of woodburning cooking stoves has been measured at between 5 and 25%; however, for actual cooking the range is probably between 5 and 10%. The amount of fuel consumed per capita varies depending on the age of the individual, the diet, and the methods of cooking. Most studies of fuel use have failed to isolate cooking requirements. Of those that have[1], the average daily consumption appears to range from 1.2 to 2 kg per capita.

Assuming a thermal efficiency of 7% and an average energy content of 3500 kcal per kilogram of air-dried wood, then the actual cooking of the food requires only 300 to 500 kilocalories per capita per day. If it were possible to increase the thermal efficiency by half then the fuel requirement would be reduced to .8-1.3 kg per day. The annual savings in fuel would be from 140 to 240 kilograms per capita. Assuming that the annual increment of above-ground wood in the tropical areas is about 5 metric tons per hectare then the average savings per household of 6 would be the amount of wood produced on 1/6 to 1/4 hectare. With rural farms averaging from 1/4 to 2 hectares in different developing countries, more efficient stoves could considerably reduce the land needed for firewood. If the cooking stove is also used for space heating during cold or rainy seasons then the fuel savings with improved stoves could be much greater. If biomass fuels other than firewood are used, then a reduction in consumption would allow for alternative uses as a fertilizer, fuel or fodder.

The design of wood burning stoves for both cooking and space heating in developed countries has improved considerably over the last two centuries through the use of new materials and engineering designs for effective heat transfer and combustion. In the developing countries the improvement in stove designs has been realized through a slower evolutionary process. As a result, metal stoves are rare and most rural stoves use direct radiant heating rather than conduction or convection.

In the last thirty years efforts have been made to introduce new stove designs in the developing countries, especially India, Indonesia, and Guatemala. These new designs continue to use non-metallic materials but introduce new heat transfer techniques. The designs have not been very successful in terms of widespread adoption primarily because the potential users did not perceive the advantage of fuel savings where such savings increased the complexity of the cooking activity.

The procedures for testing existing stove models were developed over the last twenty years. Two procedures evolved; one for determining the thermal efficiency of a stove based on the measurement of heat captured and the energy content of the fuel consumed, the other for measuring the amount of fuel required for accomplishing a given task.

The stove design and testing efforts have produced few successes but have greatly improved our understanding of how to design stoves. Much of this new knowledge relates to the design elements that must be considered in addition to the physical structure of the stove. The stove-cooking system is fairly complex. It includes physical, cultural and economic subsystems. The physical subsystem includes (1) structural components; the fuel, the stove and the cooking vessel; (2) operational components which control the rate

of combustion, the air flow through the stove, and the use of different cooking ports; (3) cooking components; the type of foods and the method of cooking; and (4) environmental components which determine the flow of heat, hot gases, and pollutants into the cooking area. This subsystem also includes the procedures necessary to cook with a relatively low rate of fuel consumption.

The cultural subsystem includes the traditional roles of the cook and fuel gatherer within the society, and the importance of cooking in the social interaction within the family and among villagers. The cultural subsystem also contains the innovation and training mechanisms within a village which would permit the dissemination of new technologies.

The economic subsystem includes the supply of local materials and labor for constructing a stove and fuels for cooking, and the local demand by rural cooks and fuel gatherers for fuel economy. This subsystem is analyzed to determine how the user selects his fuel and how carefully these fuels are used.

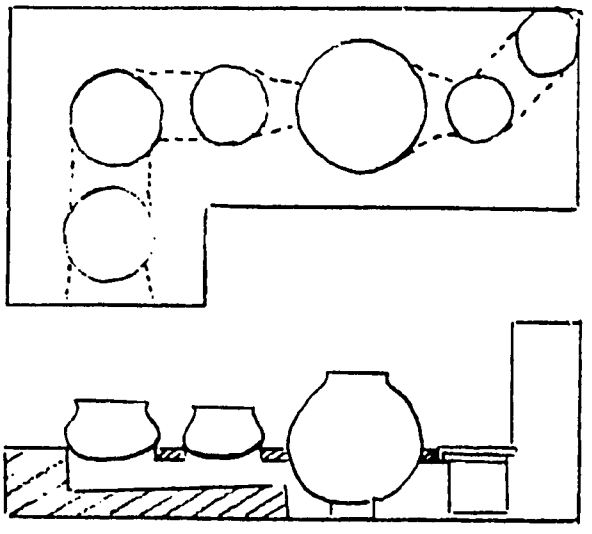
This report is not a survey of the stoves which have been examined, tested and developed. Such a survey has already been performed most admirably by Stephen Joseph and is presented in two reports, one to be published jointly by VITA and ITDG, and the other by FAO.[2] Instead this report tries to synthesize the current thinking on designing stoves for LDC's.[3] Its primary focus is the engineering problems of stove design. Towards this end, the paper is divided into seven sections; stove characteristics, perceived needs, history of stove design, stove elements, stove efficiency, design techniques, and design policies.

II. Stove Characteristics

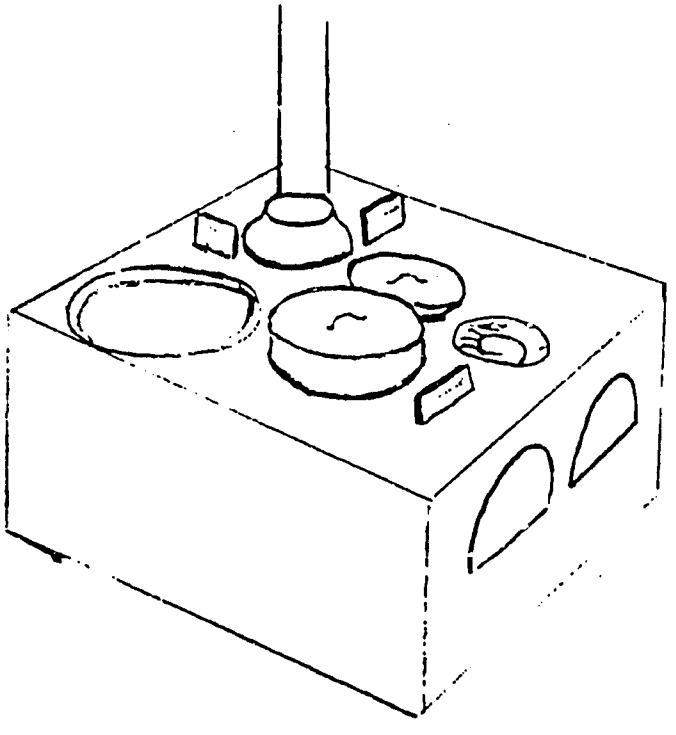
A surprising variety of stoves are used throughout the rural areas of developing countries. Within Indonesia alone dozens of models are used. Most developing countries have produced their own designs. Stove designs range the traditional three rock stove on which a pot is mounted to the larger Indian Chulas equipped with a flue and draft control. Many designs have been described in the literature and some of these models have been tested to determine their efficiency.[4] While no attempt will be made to catalogue the various types observed, it is useful to group different stoves according to their primary design elements. The elements which are most useful from a technical perspective are fuel, construction materials, heat transfer mechanism, thermal mass, form, and identifiable features.

The type of fuel used in a stove radically affects its design because of the combustion properties of the different fuels. The basic distinction between fuels is their initial phase as a gas, liquid, or solid. Within these categories distinctions can be made based on the type of combustion. The four basic rural fuels are charcoal, firewood, agricultural residues and kerosene. The first three pyrolize and generate gases which ignite. Other fuels which burn in a similar manner are rice husks, sawdust, and agricultural wastes. Kerosene vaporizes and burns as a gas. The combustion process for gasoline and alcohol is similar. Another fuel is gas but it is not much used in rural areas. Gas in the form of LPG, natural gas, and coal gas is used in urban areas while bio-gas is used to a limited extent in the rural areas. The breakdown on fuel types is shown in Table 1.

The principal materials used for construction of a stove are; sand and mud, ceramic clay, stone, brick and mortar, metal, and earth. Some stoves are built out of a combination of the above materials. The Thai charcoal stove studied by Openshaw[5] was built from a combination of ceramic

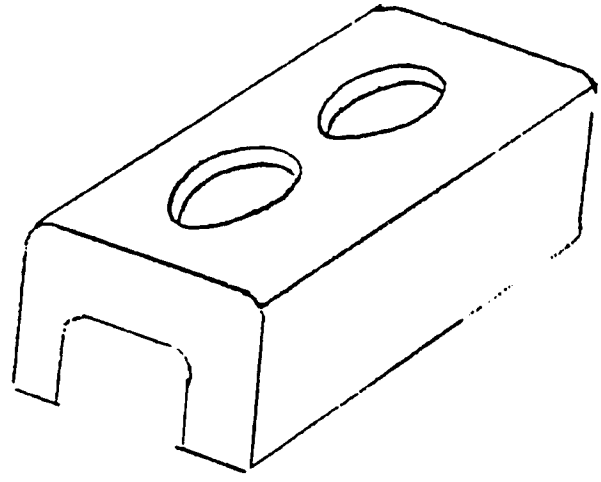


Hyderabad Chula

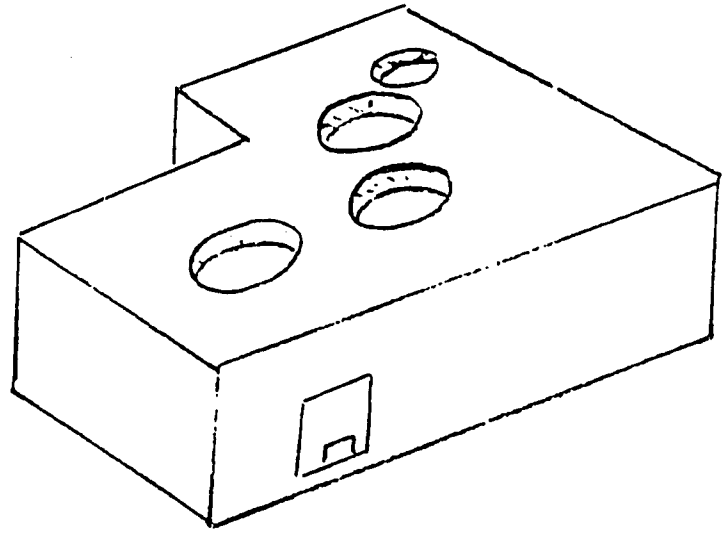


Lorena Stove

Figure 1
New Cooking Stove Models



Traditional Java Stove



Singer Stove

Figure 1 (cont)

clay, metal, and ash. The type of material affects the heat transfer properties of the stove. Part of the heat generated from combustion is transferred to the walls of the stove and subsequently to the surrounding air. The rate and quantity of heat transferred depends on the thermal conductivity and specific heat of material used. Metal has a much higher thermal conductivity than ceramic clay or mud and sand.

Stove construction is done by family members or a local artisan, depending on the complexity of the design and the type of materials used. Metal, brick and ceramic stoves are usually built by artisans. Mud and sand, stone, and earth stoves tend to be built by family labor.

The three basic mechanisms of heat transfer are radiation, conduction, and convection. The primary mechanism in rural cooking stoves is convection, in those designs where the cooking vessel is located away from the burning fuel, and radiation in those designs where the cooking vessel is positioned directly over the burning fuel. Conduction can be an important mechanism for heat transfer in earth and rock stoves, but more generally it is important only for the movement of heat through the walls of the stove into the kitchen and through the walls of the cooking vessel into the food. Many stove designs incorporate a combination of heat transfer mechanisms depending on the location of the cooking ports. These mechanisms are defined on page 16. The resulting classifications are shown in Table 1.

The thermal mass of a stove has an important effect on its efficiency for performing different types of cooking. A high thermal mass stove is useful for slow cooking and space heating. It retains a large amount of heat in the walls of the stove which is given off through radiation and convection to the air in the kitchen and through conduction and convection to the cooking vessel after the rate of the fuel combustion has decreased. A low thermal mass stove is useful for quick cooking because it requires very little heat for the stove walls to reach a stable operating temperature. The materials used in stove construction determine the specific

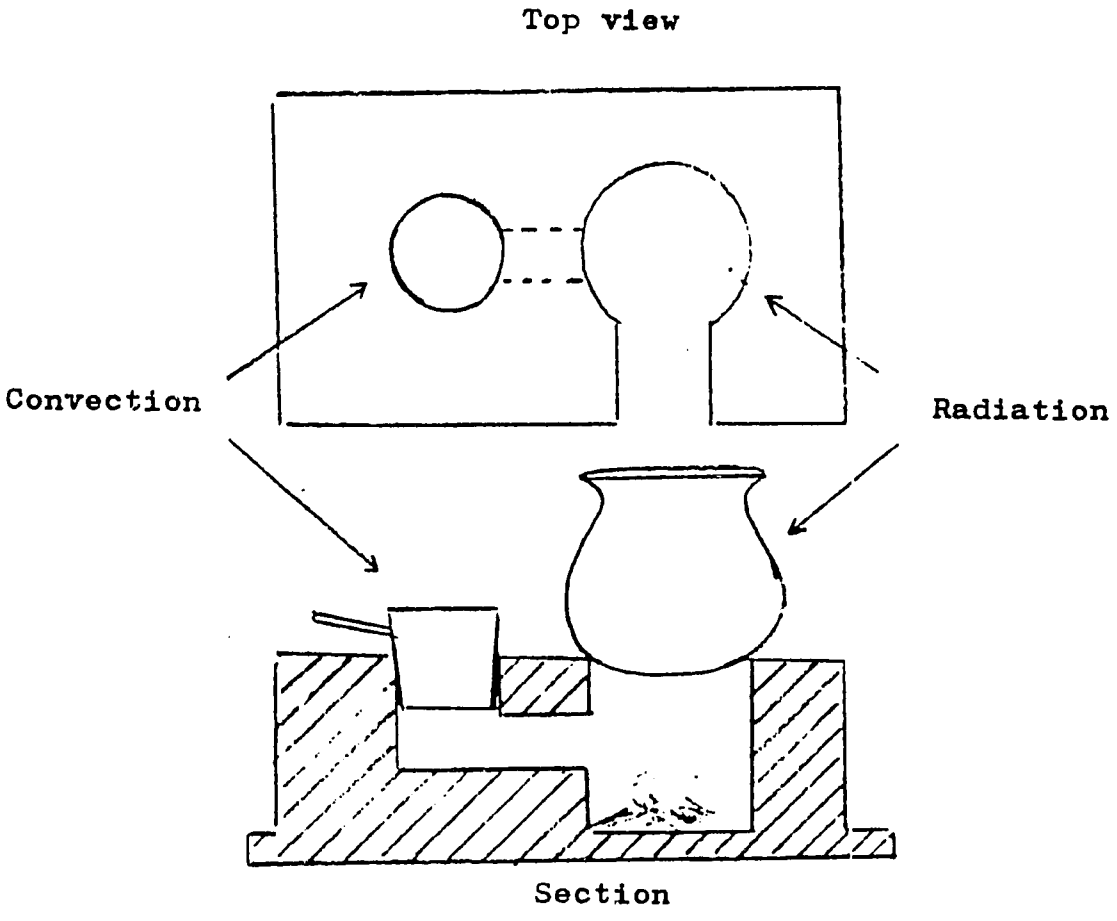


Figure 2
Convection and Radiant Heating

heat of the stove walls. The specific heat and the mass of the stove determine its thermal mass.

A stove design has a number of major form elements. One is the general configuration of the combustion and heating areas which can be described as enclosed, sheltered, or open. The three rock stove is the classic open stove, the Lombok ceramic stove in its semi-circular form is a sheltered design, and the Magan Chula is an enclosed design.

Another form element is the location of the working surface. It is usually located so that the cook is squatting, sitting, or standing. A third form element is the number of cooking ports. The simpler traditional stoves had one or two ports whereas more recent designs have three and four ports to permit more diverse cooking activities and to improve fuel efficiency.

The identifiable features of a stove include flues, dampers, grates, etc. A stove usually has a combination of these features. A checklist of features is presented in Table 1.

III. Perceived Needs

The major impetus behind the design of new stoves is to reduce the fuel requirements for performing normal cooking.

Perhaps the major reason for a low acceptance rate of more efficient stove designs has been the lack of concern for fuel conservation in rural areas. Although much attention has been given to the shortage of fuelwood in countries such as Nepal and India, the sensitivity of the rural populace to shortages of fuel supplies is not as high as energy-conscious western minds would imagine. The diminishing fuel supply is only one of many problems faced by rural people, and is surely less significant than problems of agricultural production. In many countries the rural populations have adapted to problems of scarcity by simply moving down the fuel chain from firewood to agricultural wastes and dung.

Table 1

Stove Characteristics

I. Fuel
   a. Solid
      1. charcoal
      2. firewood
      3. agricultural waste
      4. forest wastes
   b. Liquid
      1. kerosene
      2. alcohol
      3. gasoline
   c. Gas
      1. coal gas
      2. LPG
      3. natural gas
      4. producer gas
      5. biogas

II. Material
   a. Sand and/or mud (Lorena)
   b. Ceramic
   c. Brick and mortar
   d. Stone
   e. Metal
   f. Earth
   g. Metal and others
   h. Brick and others

III. Heat Transfer
   a. Direct -radiation and convection
   b. Indirect - convection
   c. Retained - conduction and convection
   d. Mixed

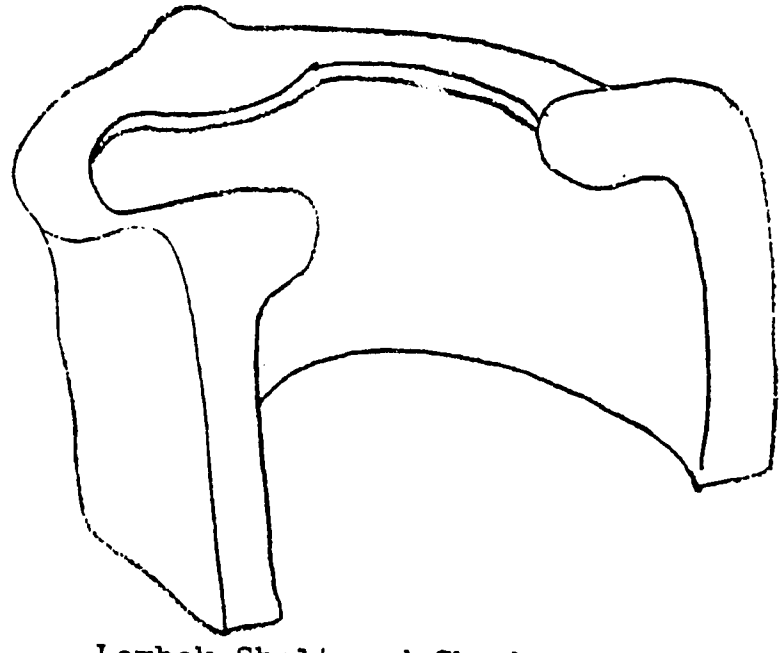
IV. Thermal Mass
   a. High
   b. Low

V. Form
   a. Combustion
      1. enclosed
      2. sheltered
      3. open
   b. Height
      1. standing
      2. squatting
   c. Ports
      1. one
      2. two
      3. three
      4. four or more

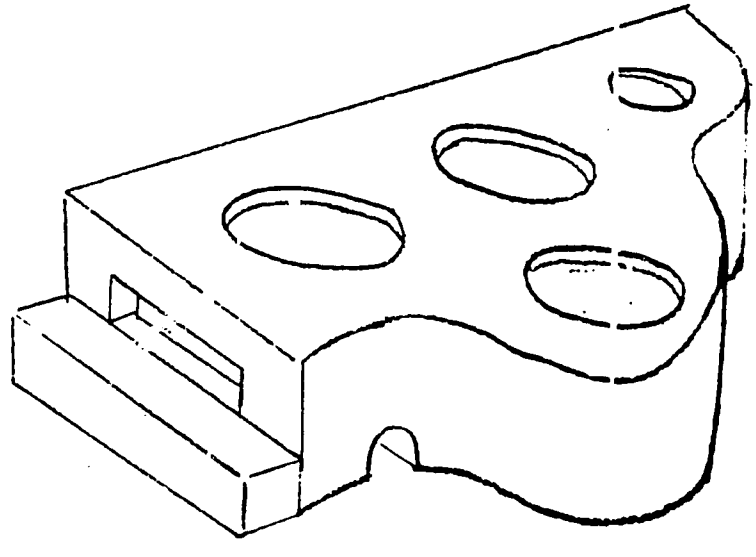
VI. Features

a. Flue
   1. with damper
   2. without damper

b. Baffles - turbulent flow
c. Baffles - tangential flow
d. Firedoor
e. Fuel grate
f. Fuel drying chamber
g. Bevelled ports
h. Special function ports
i. Oven
j. Port covers

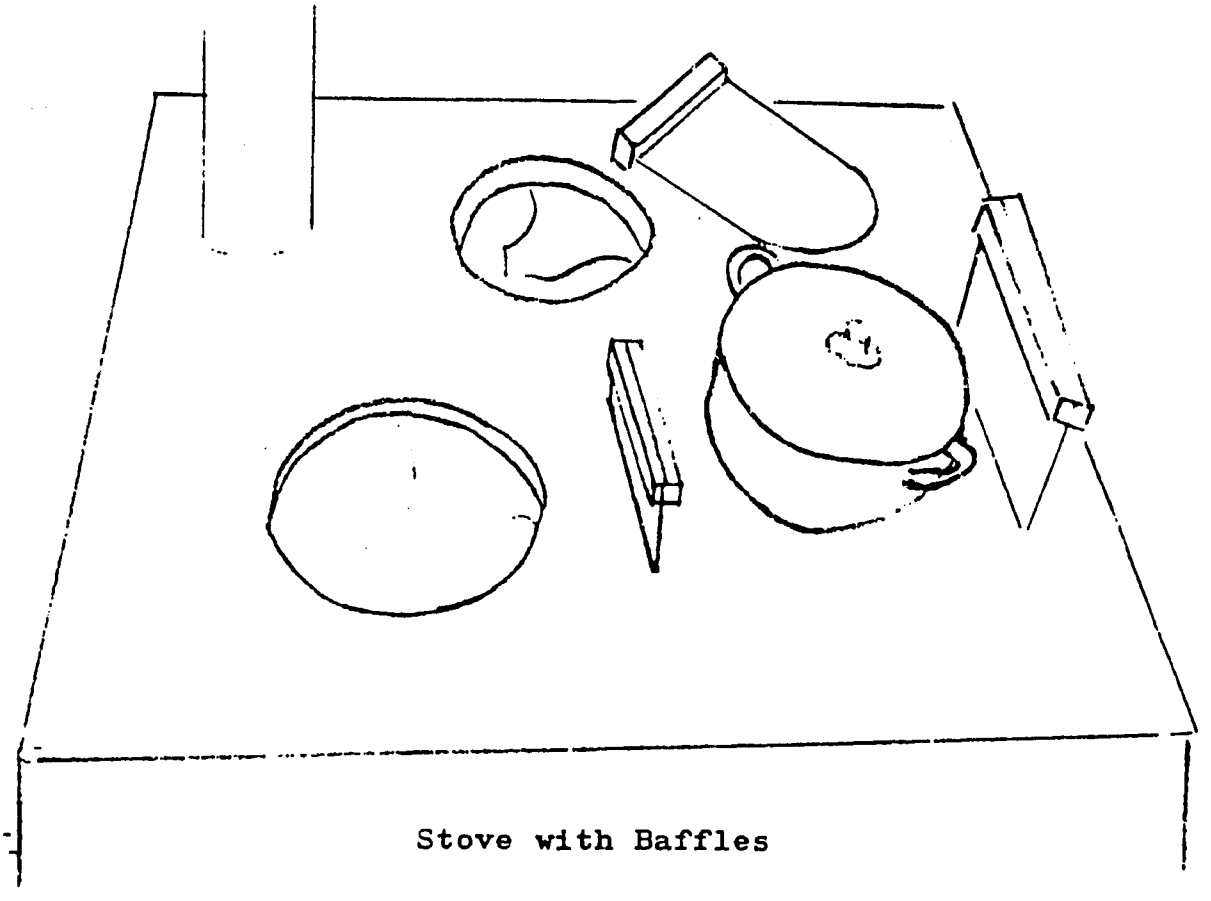


Lombok Sheltered Chamber Stove



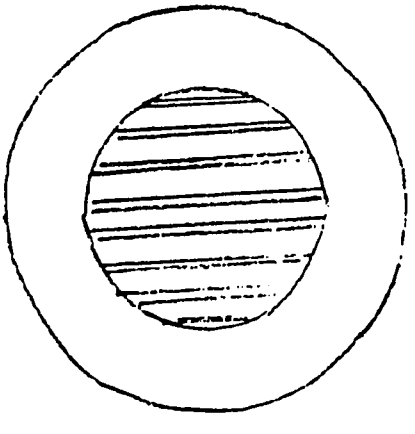
Magan Chula Enclosed Chamber Stove

Figure 3
Sheltered and Enclosed Chamber Models



Stove with Baffles

Top view



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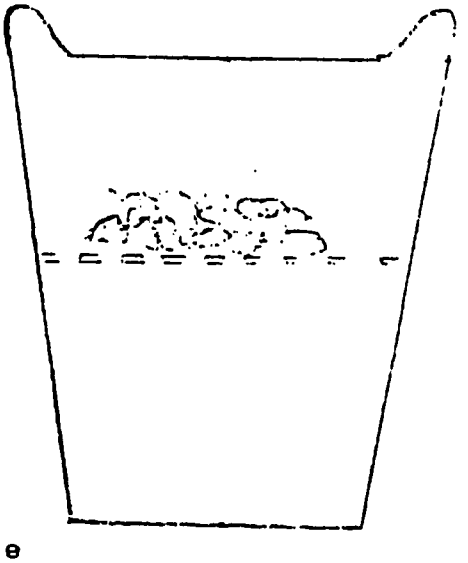


Stove with Grate

Figure 4
Stove Design Features

The major difficulty in stove design work is to gain acceptance of a new design. Some of the specific problems which have hampered previous efforts at stove designs are the failure to:

- develop designs sufficiently low in cost and simple to construct and operate;
- use local participation in developing design objectives and evaluating the new models;
- develop a design with benefits in addition to improved fuel efficiency.

In order to achieve widespread adoption of a new model, it is necessary to understand the social activity of cooking and the perceived needs of the rural cooks and fuel gatherers. These issues have been explored by Gould and Joseph, Evans, Elmendorf, Schaller and others,[6] but so far our understanding of these issues is much less complete than our understanding of the technical issues. Much has been learned from stove experiments as to what these needs might include. Evans working in Guatemala learned that the traditional designs which required the cook to work in a kneeling position were less desirable than models which permitted the cook to stand. Researchers in Bangladesh found that by removing the smoke through a flue the kitchen environment was healthier but a major preservative for thatch roofs was eliminated. Schaller in investigating the acceptance of the Lorena stove in Guatemala found that users sacrificed fuel economy to simplify operational procedures.

A VITA volunteer working in Botswana highlighted the problem of perceived needs as follows;

"It does seem that mud stoves are the first choice as an alternative cooking means but it is not clear whether the effort saved in gathering firewood, the ability to control smoke and the reduced risk in children upsetting cooking pots (all good features seen in the mud stoves) represent a significant enough improvement in cooking style

to motivate people to the point where they would actually build mud stoves on their own... My own feeling is that changes in cooking styles will likely take place slowly, perhaps over a generation rather than a few years... "

Because cooking is an important part of social and cultural traditions, it is important that the use of a new stove design does not significantly alter these traditions. New stoves should be designed with an understanding of existing cooking practices. Changes in the time and attention which must be given to cooking can modify patterns of social interaction. Traditional stoves should be studied to determine their performance characteristics and the rationale for their design. As Stephen Joseph has pointed out, "innovations based on traditional technologies usually have far more chance of success than completely unfamiliar innovations."[7]

Among issues to be considered in developing acceptable stove designs are;

- The cook stove should use fuel(s) which are readily available from local sources and which do not have greater value in alternative uses;
- The skills and materials required to construct the stove should be readily available in the rural area;
- The cost of the stove should be comparable with that of traditional stoves;
- The stove should perform acceptably all the customary cooking operations;
- The time required for cooking should be less than or equal to that for traditional stoves;
- The stove should use traditional cooking vessels or new cooking vessels which can be obtained at an acceptable cost;
- The operation of the stove should not be significantly more difficult than that of traditional stoves;
- The stove should be at least as durable as current models;
- The dissemination of the stove should be done using existing networks for training, extension, and the introduction of innovation.

IV. History of Stove Designs

Cooking stoves which burn wood have been the focus of increasing study over the last few decades. The lineage of the stove design can be seen by comparing the work of Raju in India , Singer in Indonesia , and Evans in Guatemala[8].

Raju, working with the Hyderabad Engineering Research Laboratories in the early 50's, designed a 'smokeless chula'. This design was an advancement over previous designs such as the semi-circular country oven, because it incorporated a flue for removing smoke from the kitchen, sloping ducts for improving the transfer of heat through convection, an internal damper to control the rate of combustion, an attached chamber for drying the fuel, and a raised cooking surface. A revised design was proposed in 1955 which used curved rather than straight ducts to increase turbulent flow and added a fuel grating and ash pit. This stove was called the Magan Chula.[9]

Singer, working in the early 60's for the FAO (as Raju had done) experimented with traditional Indonesian stoves and proposed a series of designs which had varying stove heights and number of ports but incorporated the same design features as Raju had introduced in the early 50's. The major change was to relocate the damper from between the ports to the entrance of the burning chamber. He conducted a number of experiments to determine the efficiency of these units using different fuels.

Evans, working in Guatemala in the 70's introduced the Lorena stove which used the same principles as its predecessors but included metal baffles which could be used to block off unused ports.

All three designs are built with mud and sand mixtures and are fueled by firewood. The designers chose construction techniques and materials which were available to local craftsmen. All three units use direct radiant heat at the first port and convection heat at the remaining ports. As a result the temperature at the ports varies. The lowest temperature port is the one closest to the flue and is usually

used to heat water. Singer did not incorporate this feature because hot water is not traditionally used on Java. The problem of different temperatures at the ports was dealt with by Penfold and Obt who redesigned the Hyderabad Chula to deliver radiant heat to all three ports by means of a common combustion chamber.[10]

The designs discussed so far are similar in their use of wood as a fuel and convection flow through a chimney. Some work has also been done on non-chimney designs over the last decade. These include Narruzaman's work in Bangladesh in which a grate was installed in a traditional ceramic stove.[11] The grate was positioned at the hottest part of the stove and is reported to have reduced fuel consumption by half. ITDG introduced a modification of a traditional Indian stove by connecting a cooking port and a tandoor oven.[12] The stove improved combustion by incorporating a combustion chamber which was self-damping when filled with wood and by using a grate to concentrate the area of combustion. It also improved heat transfer by inserting baffles to direct turbulent flow along the walls of the tandoor oven.

Other research has been conducted on stoves fueled with charcoal, with attention being given to the design of the grate and the slope of the walls for efficient combustion. Openshaw has attempted to introduce into Tanzania a charcoal stove built with a metal outer skin, ceramic-lined burning chamber, and ash-insulated middle layer.[13] This design is used in Thailand and is considerably more efficient than the metal units used in Tanzania. DeLepelaire has designed a charcoal burning stove with a double skin so that the primary air is preheated before entering the combustion chamber.[14] His design also incorporates sloped walls.

Other work on non-wood stoves include the research by Singer , Shillong , Georgia Tech, ITDG , and Volunteers in Asia on charcoal, sawdust, rice husks, and rice-hull fueled stoves.[15] In general they have modified existing designs using

different materials for construction and/or different configurations of ducts, flues, and ports.

More recent research has reexamined some of the design changes which were first introduced by Raju. The chimney was originally incorporated into the stove design to remove smoke from the kitchen and to provide a channel to move the convection heat to the secondary ports; however, this chimney also provided a path through which the hot gases can escape. Jagadish and Shri Somasekhera working in India, analyzed the relative efficiencies of a smokeless chula and a traditional three port stove without a chimney and found that the efficiency of the unit with the chimney was not noticeably greater.[16]

The National Building Organization of India (NBOI) and researchers at Princeton have examined the effects of reducing the distance between the bottom of the cooking vessel and the source of heat.[17] The cooking vessel can be set lower into the stove when heating is by convection rather than radiation. Dutt, working with a three port smokeless chula, found that the embedded cooking vessel located at the port closest to the chimney absorbed more heat than a smaller cooking vessel located nearer to the combustion chamber.[18] The embedded vessel was surrounded by a cooler convection heat whereas the smaller vessel had less surface area exposed to a hotter convection heat.

The previous research on stove design has examined all the major physical design features, including:

1. Number of ports
2. Use of convection rather than radiant heating
3. Configuration of ducts to conduct heated air under and around the ports and through to the flue
4. Flues
5. Dampers
6. Grating
7. Fuel drying chamber
8. Baffles

Much of the in-country design work over the last three years has focused on the redesign and dissemination of the Lorena stove. Efforts are currently underway by Evans and others to introduce variations of his design into Senegal, Sri Lanka, Indonesia, Nepal, and Upper Volta, among others. While the stove's mass has been reduced and the configuration of the ports rearranged, the design elements remain the same. Stephen Joseph has just completed an examination of mud and sand stoves including the Lorena at his laboratory in Reading, UK. He is now experimenting with various ceramic stove designs. Other stove testing and design projects are being conducted at various locations around the world, most notably at ASTRA in Lucknow, at the Catholic University in Louven, and in Bangladesh under the direction of Nural Islam.

V. Elements of Stove Design

A cooking stove despite its simple form embodies a rather complex technology. The technology can be broken down into two processes, combustion of the fuel and transfer of the heat of combustion. The cooking system contains three components; the stove, the fuel, and the cooking vessel with its contents.

1. Combustion

The combustion of fuels in cooking stoves can be defined as the oxidation of carbon compounds in an exothermic reaction taking place at a temperature above the compound's ignition temperature and producing visible and infrared radiation, carbon dioxide, and carbon monoxide.

The combustion of wood takes place in stages. As the surface of the wood is heated up it undergoes pyrolysis, the chemical breakdown of lignin and cellulose to produce charcoal. The pyrolysis activity has four stages. Up to 200°C

the wood becomes dehydrated and water vapors and other non-combustible gases are produced. Between 200°C and 280°C, active pyrolysis takes place in which combustible gases such as carbon monoxide, methane, formic and acetic acid, methanol, and hydrogen are produced and carry with them to the surface droplets of inflammable tars. The residue left after this reaction is charcoal which at temperatures above 500°C glows red and is consumed.

The layer of pyrolysis moves inward as the temperature within the wood rises. Eventually all the gases, tars, and water vapor are driven out. Once the combustion of the gases and tars is complete than the remaining charcoal begins to burn visibly.

The spontaneous ignition temperature of the gases is 450°-550° C and once ignited they burn at a temperature of 1100°C. The tars ignite at a somewhat lower temperature, but the charcoal formed during pyrolysis ignites at only 150°C and burns at a temperature of 500° C-800° C . Shelton has theorized that the ignition of the gases occurs because they are heated to their spontaneous ignition temperatures as they pass through the charcoal layer.[19] Once ignited these gases produce sufficient radiant energy to maintain combustion.

In addition to adequate temperature the combustion process requires sufficient oxygen, which is provided by circulating air through to the fuel. If there is too little air then there is not enough oxygen for the carbon molecules to react with. If there is too much air then the density of carbon molecules is too low to maintain combustion. The ratio of gas-to-air which can sustain combustion can vary between a range known as the flammability limits. These limits vary depending on the fuel being burnt. Even where there is enough air to maintain combustion, the combustion may be

incomplete. (Complete combustion occurs when all carbon is converted to CO_2 and all hydrogen to H_2O.)

The volatile gases and tars ignite well above the surface of the wood. The escaping gases push air away from the surface of the wood, and the volatile gases must then travel farther to obtain sufficient oxygen for combustion. The primary air must be brought in above the burning surface but not so far away as to allow the volatile gases to cool below their ignition temperature. Since the ignition temperature of charcoal is well below its melting and boiling points the charcoal ignites as a solid, and burns at the surface with little or no flame. This description of the combustion process was complied from the reports by Shelton, Joseph, Kanury, and Browne.[20] More detailed descriptions are available in their reports.

The combustion of agricultural residues has not been studied in detail but the chemistry of these residues is similar to wood and the process should be similar.

2. Heat Transfer

The design of cooking stoves has as its primary goal the efficient transfer of the heat generated by combustion to the food contained in the cooking vessel. Heat transfer is accomplished by three mechanisms:

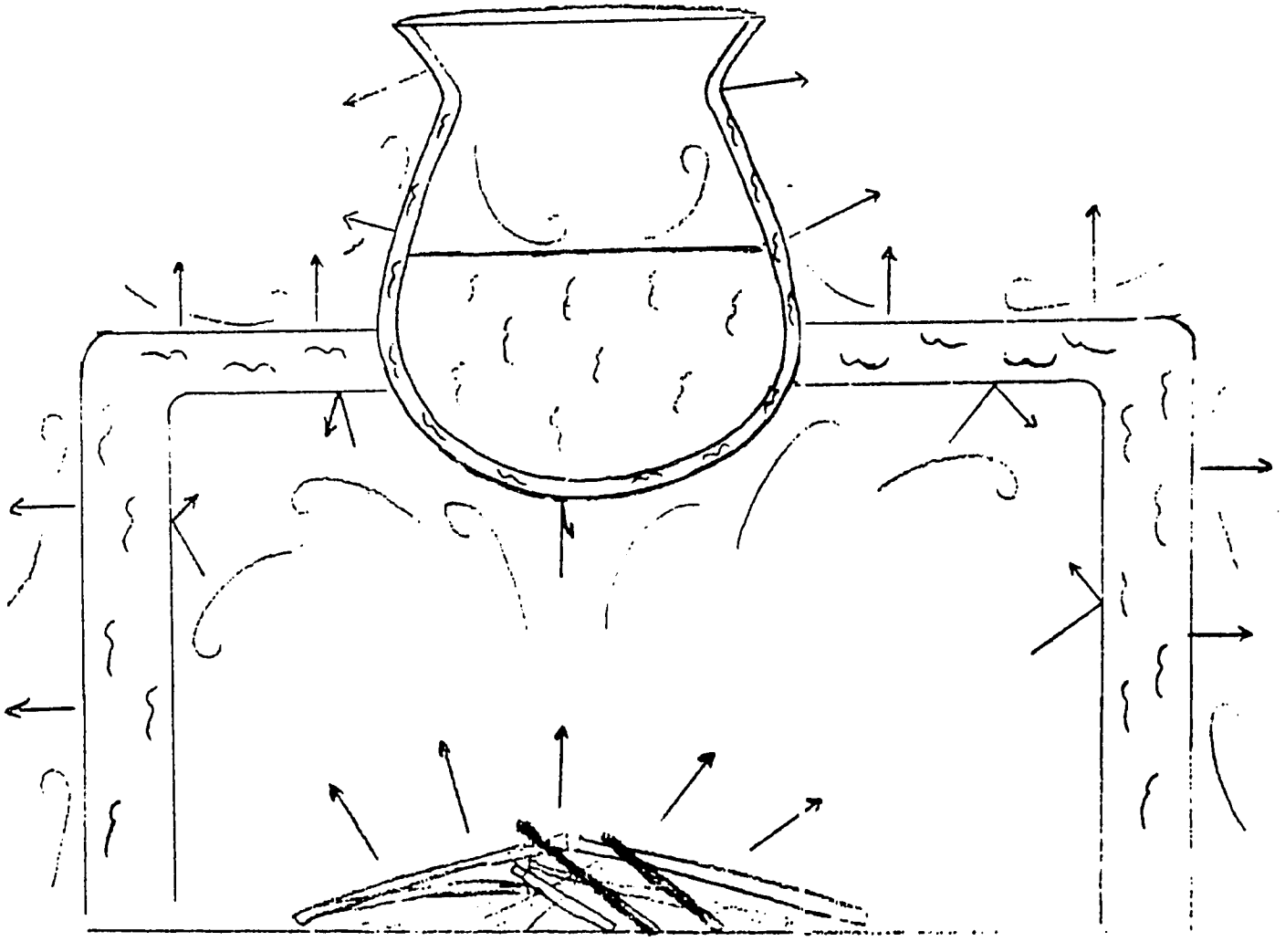
Conduction - is the exchange of kinetic energy from regions of high temperatures to regions of low temperature through the direct collision of molecules: The heat flux if determined by the temperature gradient and the thermal conductivity of the material. Conduction is involved in the transfer of heat through the stove walls, through the walls of the cooking pots, and between the two.

Convection - is the exchange of heat between a fluid flow and a solid body which have different temperatures. The heat flux depends on the physical properties of the mediums, the difference in temperature of the two mediums, and the velocity and type of

flow--laminar or turbulent. The first and third factors are incorporated into the heat-transfer coefficient. Convection is involved in the transfer of heat between the combustion gases and the walls of the stove and cooking vessels, between the stove walls and the surrounding atmosphere, between the cooking vessel and the surrounding atmosphere, and between the walls of the pot and the cooking liquid.

Radiation - is the exchange of heat between two bodies at different temperatures through electromagnetic radiation at wavelengths and in a quantity determined by the absolute temperature of the two bodies. The heat flux is a function of the fourth power of the absolute temperature and the reflective properties of the surface of the two bodies (their thermal emissivity). Radiation is involved in the direct transfer of radiant heat from the zone of combustion to the walls of the stove and cooking pots and from the heated walls of the pots and stoves to the surrounding atmosphere.

A basic diagram of the heat transfer mechanisms is shown in Figure 5. Heat is transferred to the cooking pot by direct radiation from the combustion chamber, convection from the combustion gases, and conduction from the stove walls. The major heat loss is through the passage of hot combustion gases out of the stove's exhaust port and into the surrounding atmosphere. Heat losses also occur through radiation and convection from the stove and cooking vessel walls to the surrounding air, and through conduction from the base of the stove to the earth. Another significant heat loss is the latent heat stored in the body of the stove. The quantity of latent heat is determined by the temperature of the stove walls and the specific heat and mass of the stove



radiation

convection

conduction

Figure 5
Methods of Heat Transfer

materials. The rate at which the stove stores latent heat can be determined from the specific heat and thermal conductivity of the stove materials.

The heating of a cooking stove can be separated into three phases. In the first phase the fuel is ignited, the temperatures of the combustion chamber and stove walls rise, and the rate of heat generation increases. The heat in the stove walls is then conducted to the outside surface where it is transferred to either the cooking vessel or the surrounding atmosphere. The second phase occurs when the stove and cooking vessel reach an equilibrium temperature and the fuel is burning at a relatively constant rate. The third stage occurs when the burning rate of the fuel decreases and the stove and cooking vessels begin to lose their latent heat.

It is not possible to model thermodynamically the complete cooking activity; however, a model of specific heat transfer mechanisms under specified conditions of heat generation and initial temperature can be designed to analyze the effectiveness of stove design. ITDG is sponsoring work at Imperial University to model heat convection from the flow of combustion gases under adiabatic conditions.[21] Dutt at Princeton has examined the losses of heat through convection and radiation from the cooking vessel to the surrounding atmosphere.[22]

3. Fuel

The biomass fuels which are burned in cook stoves include wood, charcoal, agricultural wastes, wood wastes, and dung. The chemical energy content of a fuel can be measured in a bomb calorimeter[23]. Different species of

wood have differing densities but approximately the same energy content, about 4500 ± 300 kilocalories per kilogram (18,800 ± 1250 kilojoules).[24] Other lignin and cellulose based fuels such as agricultural residues have similar energy contents. The characteristics of a fuel which affect the way it burns are density, moisture content, size, surface-to-mass ratio, and ash content.

The effect of density is not well understood. It is known that lower density woods and agricultural residues are easier to ignite, are consumed faster (where the measurement is volume per unit time), sustain their own flame sooner and produce less charcoal and more gases. The burning rate, weight consumer per unit time, varies for different species of wood but this variance may not be significant as suggested in experiments by L. Metz.[25] The variation for residues is not known.

The moisture content of a fuel affects the rate at which it burns and the amount of heat released. The higher the moisture content, the lower the amount of heat that is available for cooking. Part of the weight of the fuel is water which does not burn. Some of the heat generated from combustion is needed to evaporate the water and maintain it in vapor form until it leaves the stove. With wood additional heat is absorbed in an endothermic reaction of some of the escaping water vapor with the surface charcoal to form CO and H_2. The water vapor also dilutes the escaping gases and tars generated by active pyrolysis thereby making them harder to ignite. Because water has a higher thermal conductivity than wood, heat is conducted more rapidly from the wood's surface into its center thereby increasing the time required to bring the outer layer of wood to the temperature of active pyrolysis.

The size of a piece of fuel affects the ability of that fuel to maintain combustion. For wood over 2.5 cm in diameter the flame is not self sustaining because the wood has sufficient thermal capacity to cool the surface below the ignition tempera-

ture. Where pieces of wood greater than this diameter are used it is necessary to place additional pieces nearby so that the heat radiated from juxtaposed pieces will maintain the surface temperature.

More important than the diameter is the surface-to-mass ratio. The larger the surface area the more heat that will be absorbed with a uniform heat intensity. The less mass per unit surface area, the more rapid the rise in temperature of the fuel with a given heat intensity. Also the larger the surface-to-mass ratio the easier it is to dry a fuel. Agricultural residues are low density, high surface-to-mass ratio fuels which burn quickly with a self-sustaining flame.

The non-combustible residue from a burnt fuel is ash. For wood the ash content ranges from .1% to 3%. For charcoal and agricultural residues the ash content is higher.

Careful drying, cutting and positioning of fuels for use in a cook stove can increase the percentage of the fuel's energy content that is transferred to the cooking vessels, however this selection and preparation involves extra work. The drying of a fuel is very important for reducing problems of ignition and loss of latent heat in water vapor. Drying requires storage of the wood in a protected area for several weeks or months. In rural areas fuels are collected as required. The maximum inventory for home use is no more than a week's supply. Constructing a drying shed and maintaining an inventory require time and space. If the fuel is purchased rather than collected then there is a financial cost for maintaining the inventory.

The surface-to-mass ratio of wood can be increased by splitting the wood. Splitting wood involves additional work unless it is already required by the size of the combustion chamber. In most rural areas the size of the stove and the short time during which cooking is performed require the use of small pieces of wood and agricultural residues. Where wood is sold commercially larger pieces of wood are gathered, split into smaller pieces, and stacked, but the cost of this labor is included in the price.

Rural cooks have a good understanding of how to arrange fuel for efficient combustion in traditional stoves. The more traditional designs such as the three rock and Java stoves allow the pieces of fuel to be moved periodically so as to maintain the rate of combustion and focus the flame under the cooking vessel.

4. Cooking Vessels

The design of cooking vessels has a major impact on the use and efficiency of cooking stoves. The shape and material of the vessel determine the surface area exposed to heating and cooling by radiation and convection. The flow pattern of gases moving around the vessel and up alongside the port determine the type of cooking which can be done.

For cooking vessels which are heated by radiation the greatest heat transfer is obtained with a flat bottom and dark colored exterior. The closer the bottom of the vessel is to the source of radiation the greater will be the solid angle of radiation subtended; however if the vessel bottom is too close to the flames then it will quench the flames and reduce the percentage of gases which are ignited. If the bottom of the vessel is black rather than shiny then it will absorb more radiant energy, but if the blackness is from a layer of carbon which also insulates the bottom then it will reduce the amount of absorbed energy which is conducted into the vessel.

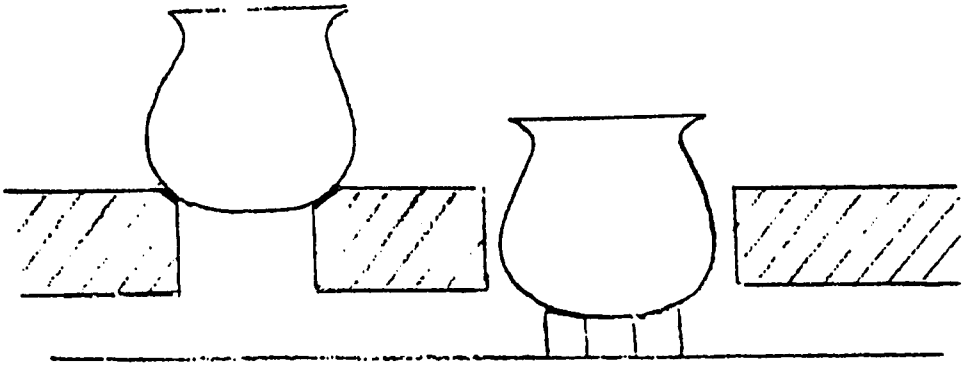
For vessels which are heated by convection from the flow of combustion gases, the transfer of heat will be improved by increasing the surface area that is exposed to the flow, the conductivity of the surface, the turbulence of the flow and the time the gas spends near to the vessel. The surface area can be increased by rounding the bottom of the pot, adding fins, and setting the pot deeper into the flue. The conductivity of the vessel can be improved by using metal rather than ceramic pots and by maintaining a clean surface. The turbulent flow and resi-

dence time of the combustion gases can be increased by appropriate stove designs as discussed in the next section.

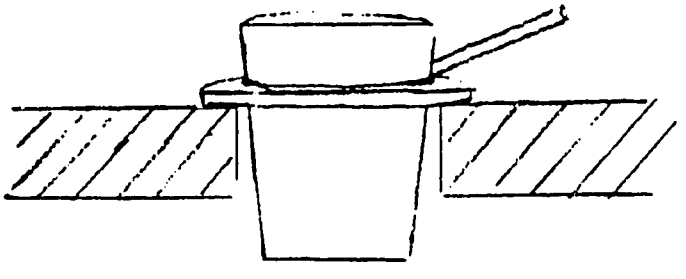
The loss of heat from the cooking vessel to the surrounding atmosphere occurs through radiation and convection at the surface of the vessel and its contents. The use of lids and pressure cookers can reduce this loss. Decreasing the exposed surface by shaping the vessel and setting it deeper into the stove can also reduce the loss. Other losses occur from combustion gases moving upwards past the cooking vessel to the surrounding air. This loss is minimized by careful fitting of the vessel into the port so as to create a seal. The port's rim can be bevelled to fit a rounded vessel bottom or the vessel can be equipped with a ring support which overlaps the port and supports the vessel (see figure 6).

The design of a cooking vessel not only affects its heat transfer properties but also the method of cooking, the amount of food which can be cooked, and the handling, cleaning and storage of the vessel. The standard vessel is a pot in which grains and vegetables can be boiled or simmered. Other vessels are used for steaming or frying. More than one course can be cooked over a single port through the use of multiple-compartment vessels or through vertical stacking of vessels. These cooking vessels can be designed to hold different quantities of food but an increase in volume must be accompanied by an increase in the surface area exposed to radiant or convection heat and very often by an increase in the diameter of the cooking port. Cooking vessels can be designed with handles for serving food. They can be designed to stand upright when full for storing food. These features add to the convenience of using the vessel but may also affect its heat transfer properties.

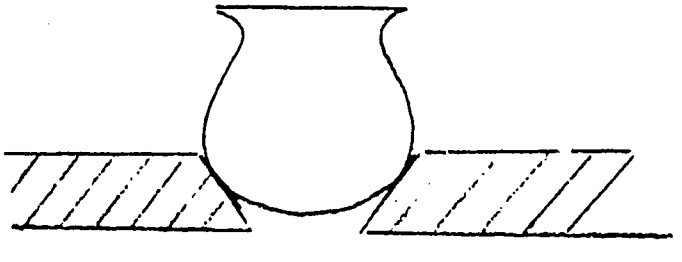
The benefits of using metal vessels for cooking have been known for several millenia. Their principle advantage relative to other vessels is greater heat conductivity. Although metal vessels are more durable they are also more



Surface and Embedded Pots

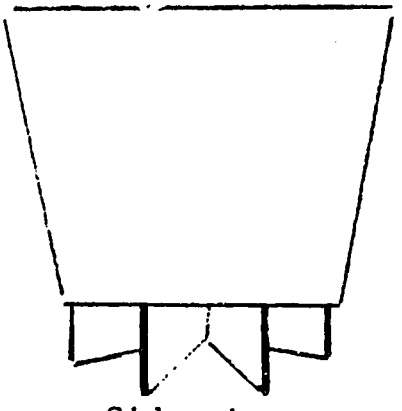


Pots with Sealing Ring

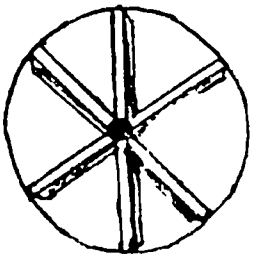


Bevelled Ports

Figure 6
Pot Designs

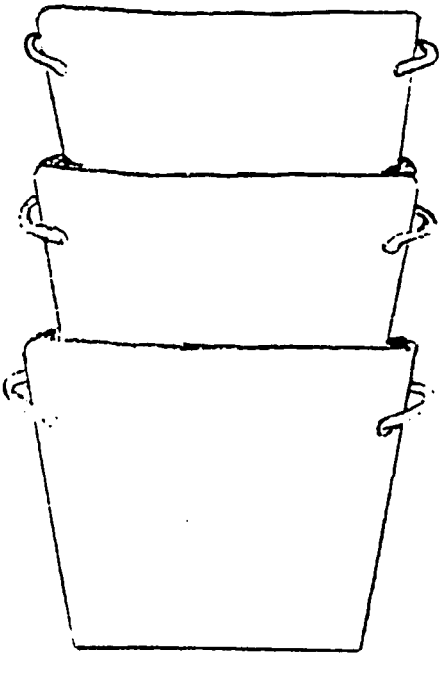


Side view



Top view

Pot with Heating Fins



Stacked Pots

Figure 6 (cont)

costly and require cleaning to prevent carbon deposits from insulating the heating surface.

Aluminum pots which can be locally fabricated have largely replaced ceramic pots in many rural areas. However, the standard designs appear better suited to conductive or radiate heating on gas and electric stoves. Little effort has been made to modify these pots for use on non-metal wood stoves. The introduction of fins, sealing rings, non-insulating black coatings, narrow necks, or vertical stacking could improve the convective heat transfer.

5. Stoves

The functions of fuel and cooking vessels, combustion and heat transfer are integrated in the structure of the stove. The stove includes a combustion chamber, a flue,[26] one or more cooking ports, a primary air inlet and combustion gas exhaust port.

The primary purpose of a combustion chamber is to protect the burning fuel from wind. To fulfill this purpose the chamber may be a simple shield or an enclosing structure. The enclosed combustion chamber must be small enough to hold the embers in a tight group, concentrate the heat and raise the temperature around the burning fuel, but large enough to allow for closing a firedoor at the inlet of the chamber. Since about 80% of the heat generated during combustion is in the form of radiant energy, it is important that the walls of the combustion chamber either reflect this energy back into the chamber or absorb and re-emit the energy without it being conducted through the walls. A reflective surface can be used but it is difficult to maintain. Alternatively the walls can be designed to re-emit energy by insulating them with firebrick, burnt ash, or other materials which minimize conduction losses.

The combustion chamber must receive an adequate supply of primary air to maintain combustion. This primary air can be

circulated from below the fuel by means of a ceramic or metal grate. The grate also offers advantages in removing ash and concentrating the zone of combustion. Where a grate is used the walls of the combustion chamber must be sloped in order to avoid quenching the flames. The required dimensions for grates and combustion chambers have been established through experience.

The flow of primary air can be controlled by dampers placed in the firedoor, the flue, or the exhaust port. The primary air can be preheated in order to obtain more complete combustion of the volatile gases, however, the ignition temperature of these gases is on the order of 500° C and it is difficult to preheat the primary air to a temperature close to that level. Secondary air can be introduced into the combustion chamber in order to increase the combustion of volatile gases when the primary air flow is restricted to reduce the rate of burn, but in most stove designs the primary air is not restricted to that degree.

The location of the cooking ports with respect to the combustion chamber determines the mechanism of heat transfer. Where the port is located directly over the combustion chamber most of the heating will be through radiation. When a cooking vessel is set into a port it must be sufficiently far from the flames to prevent quenching, a process in which the walls of the vessel reduce the temperature of the volatile gases below their spontaneous combustion temperature.

Where the port is located away from the combustion chamber, heating is through convection from the heated gases which pass through the flue beneath the port. The cooking vessel should be set well into the port to maximize the surface area exposed to these gases. In order to ensure a high rate of heat transfer across the boundary layer between

the hot gases and the pot surface it is necessary that a turbulent flow be established. This turbulence assures a continuous replacement of the hot gases adjoining the boundary layer so there is a continuous supply of heat. The turbulence can be generated by the shape of the pot, the shape of the flue and/or the introduction of baffles into the flue.

The quantity of heat transfered from a given volume of hot gas to a cooking vessel can be increased by extending the time the gas spends in contact with the cooking vessel. The residence time of the gas in the area of a cooking port can be increased by swirling the gases around the port. However, the amount of heat which can be removed from the hot gases is limited. If the gases are cooled too much they will not have the buoyancy required to rise up through the flue and out the exhaust port. Also if the gases are cooled below a temperature of 180° C the tars and water vapor carried in the gases will condense on the walls of the flue and exhaust outlet. The creosote that is formed is not only highly corrosive but also a potential fire hazard.

The exhaust port of a stove at the end of the flue may be a simple opening or a chimney. The latter channels the smoke away from the cooking area but it also increases the required temperature of the escaping gases and can cause a chimney fire if not properly cleaned. The design of a chimney is well understood and it can be used to improve the draw of primary air into and heated gases out of a stove. Without a chimney the flue must be designed with sufficient slope to direct the gases towards the exhaust port.

A stove must be designed not only for efficient heat transfer but also for ease of operation and maintenance. It should be built from locally available materials, using local skills, to burn local fuels and satisfy local cooking requirements.

Operation becomes more difficult with stove designs that incorporate dampers, movable baffles, cooking port covers, and/or firedoors. For traditional stoves the fire can be observed directly and controlled by moving the fuel in or out of the combustion zone. Loading of the fuel is accomplished by pushing several sticks into this zone, placing their ends together, and igniting them with kerosene, paraffin, or kindling. In newer designs with enclosed combustion chambers and firedoors not only is visibility limited, but combustion is controlled by regulating air flow rather than fuel.

The cooking requirements are generally expressed in terms of a desired temperature and a period of time over which this temperature is needed. Traditional stoves offer a relatively simple mechanism for controlling temperature, adding or removing fuel from the fire. For multiple port stoves which use convection heating the regulation of temperature becomes much more difficult. The temperatures at the ports increase the closer the port is to the combustion chamber. The number of cooking ports in use and the types of cooking vessels used also affect the amount of heat which is available at the ports. Movable baffles and other methods of controlling port temperature add to the difficulties of operating the stove.

Ease of operation should extend to loading, igniting, and extinguishing the fuel. The combustion chamber should be designed with an entrance large enough to accommodate the pieces of fuel normally prepared for cooking. This chamber should be designed for quick ignition of fuels without using petroleum-based fuels for starters.

The ability to save the charred and unburnt fuel left after cooking is important, especially with short term cooking where a high heat is desired up until the cooking activity ceases. Fuel can be conserved if it can be easily removed from the combustion chamber and doused in the earth or

extinguished in the combustion chamber and left as a bed of charcoal with which to start a subsequent fire.

Stove maintenance activities include removing of ashes from the combustion chamber and blockages in the flues, cleaning the exhaust port or chimney, patching the stove walls when cracks occur especially around the cooking ports, and replacing grates or other features which have a life expectancy less than the stove. The more complex designs tend to require more work on maintenance. Durability is also an important design parameter. Thin walled metal stoves and light ceramic stoves tend to last a year or less. Simple stove designs tend to have a short life expectancy but are inexpensive to replace. More elaborate designs tend to be more expensive and therefore should last longer. The cost of replacing a stove depends on who is building it.

The complexity of stove design and the materials required for fabrication will determine whether a unit is constructed by artisans or by the family. If traditional stoves are constructed by the family it may well be difficult to introduce new designs which must be built by artisans.

The fuels which are commonly collected often have a high moisture content and an awkward shape. The combustion chamber should be designed to accept these fuels. Where drying is not done for a sufficient length of time, it may be desirable to use the waste heat lost through the stove walls and the exhaust port to dry new fuel.

The importance of operational simplicity can be best understood by comparing the traditional three rock stove with a modern Lorena stove. The traditional three rock stove has certain advantages. It requires no initial cost, is portable, and easy to maintain. Temperature control can be accomplished by adding and removing fuel. While fuel ignition presents some problems the fuel can be easily extinguished. The stove is located near to the ground but this is the preferred position in much of Africa. There is no difficulty in adjusting the size of the combustion area to receive locally collectable fuels and the size of the cooking port to fit any pot size.

The rocks absorb heat which then preheats the primary air and later heats the pots as the fire dies down. Although its fuel efficiency is low, considerable reduction in fuel consumption can be achieved by shielding the stove from the wind and by careful control of the flame area.

The Lorena uses less fuel than the traditional stove if properly operated, however it must be constructed by a craftsman and is not portable. It has multiple ports which must be either used or shut off with baffles in order to obtain good fuel efficiency. The size of the cooking ports is fixed although adjusting rings can be used. The stove has a relatively large thermal mass which reduces its efficiency for short term cooking. It uses a chimney which must be cleaned. Temperature is controlled by a damper. The combustion chamber is enclosed, which restricts the loading of fuel and removal of ashes. Although fuel consumption can be reduced by 1/2 or possibly 2/3 by careful operation, the control of the fire is more difficult and the stove requires more attention.

VI. Stove Efficiency

The primary means for testing the 'efficiency' of different stove designs is to measure the quantity of fuel required to perform a specific task. The task most often chosen is to raise the temperature of a known quantity of water to the boiling point and to evaporate a part of the water. The efficiency measure is calculated by determining the amount of fuel burned and the quantity of heat captured in the water.

The chemical energy content of the fuel is determined by measuring the moisture content through oven drying of a sample of the fuel and then burning the dried fuel in a bomb calorimeter. The calorific value of the dried fuel will vary somewhat with the species and with the sections selected (bark, trunk, root, leaves). However, these variations are usually within ± 15%. An even greater variation results from differ-

ences in moisture content which typically range from 15% to 40%. Most experimenters have failed to report the moisture content and chemical energy of the fuel used. If these two factors are held constant for a series of experiments then relative measures of efficiency can be developed, however, it is very difficult for other researchers to make comparisons without explicit knowledge of moisture content and chemical energy content.

The type of cooking vessel, its condition and contents can also affect the amount of heat captured. Generally the content is water and the vessel is an aluminum pot with or without a top. As already pointed out the shape of the bottom of the pot can affect the heat transfer. The way the pot sets into the cooking port, the extent to which it forms a proper seal and the surface area which extends into the flue all affect the amount of heat transfered. If a pot is used for repetitive experiments the heat transfer coefficient of the pot may change as the bottom of the pot builds up a layer of insulating carbon. The size and shape of the pot are very rarely specified by researcher experimenters so that other researchers have difficulty comparing results.

While the performance of the stove is what is actually being tested, this performance can vary with the attentiveness and technique of the operator. An experimenter may be able to coax much better efficiency out of a stove than a rural cook. Rarely does the experimenter establish standard procedures for operating different stove models. The condition of the models being tested can also vary. New stoves may not have built up a layer of char in the interior surfaces of the stove. Older models may have cracks, blockages, or changes in the dimensions due to repeated heating and cooling.

The actual measure of 'efficiency' is usually expressed as the ratio of the heat captured in the water to the energy content of the fuel consumed multiplied by 100%. The energy

content of the fuel consumed is expressed as

$$(w_i - w_f)e/(1+m)$$

where w_i and w_f are the initial and final weight of the wood used for combustion, e is the calorific value of the oven-dried fuel per unit weight and m is the moisture content of the fuel computed as the weight of a sample of the fuel before oven-drying divided by the weight of the sample after drying less 1 (expressed as a decimal). A more precise definition of the energy content not converted to heat can be obtained if the uncombusted fuel is divided into unburnt and charred fuel and the energy content of each is computed.

The heat captured in the water is calculated based on the rise from ambient temperature, t_i, to boiling temperature, t_f, and the initial and final volume of water in the pot, v_i and v_f, respectively. The formula is a rather standard one;

$$c_p v_i (t_f - t_i) + h_w (v_i - v_f) d_w$$

where c_p is the specific heat of water, d_w is the density of water and h_w is the latent heat of vaporization for water. Where more than one cooking vessel is used in an experiment, separate calculations are made for each and the results summed.

For all boiling water experiments two of the four parameters- quantity of water heated, quantity of water evaporated, quantity of fuel burned, or time over which combustion takes place-are held constant and the other two are measured. The standard experiments that have been conducted are;

1. to heat a fixed quantity of water using a fixed amount of fuel with time as a variable;
2. to bring a fixed quantity of water to the boil repetitively without evaporating the water using a fixed amount of fuel;
3. to heat a fixed quantity of water for a fixed period of time with the fuel used as a variable;

4. to heat a fixed quantity of water until it is all evaporated with time and fuel consumed as variables.

The pioneering work in measuring the efficiency of rural stoves was performed by Singer[27]. First he measured the moisture content, caloric potential, ash and stable carbon content of eleven different fuels, then he used these fuels in various stove designs and measured the amount of heat captured in boiling water at each port. Next he measured the flue gases to determine the loss of heat from gases flowing out of the stove and the completeness of combustion (quantities of carbon monoxide, hydrogen, and carbonic acid). Finally he measured the amount of time required to consume 2.1 kilograms of fuel and the amount of water evaporated from 2 liters heated in an aluminum pot.

Singer also performed standard cooking tests using fixed menus for the morning, midday, and evening meals and recorded the fuel requirements and cooking times. Whereas the lab experiments showed about a four-fold increase in efficiency of the new designs over the traditional stoves, the cooking tests showed the wood consumption for the traditional stoves was less than three times greater than that of the new designs.

The NBOI examined several wood and charcoal burning stoves using the four experiments described above.[28] After the different stoves had been tested, two were chosen to be tested for the effects of changing the design parameters. The parameters considered included the clearance between cooking vessel and stove top, the slope of the ducts, the shape of the flue, and the interior insulation of the stove. The same efficiency measurements were used in these experiments. A final experiment was performed on all of the stove designs using a cooking test with a fixed menu. The most efficient stove based on the lab tests required the greatest amount of fuel for cooking because of the rapid rate at which the fuel was burned. Despite the number of tests conducted the results

Figure 7

Singer's Stove Test Results

TEST	1	2	3	4	5	6
WOOD	Acacia	Acacia	Mangifera	Pinus	Hevea	Cocos
Wood consumed kg	2.1	2.1	2.1	2.1	2.1	2.1
Caloric power kcal/kg	3,529	3,529	3,399	3,772	3,482	3,501
Duration of the test mins.	60	65	50	105	105	110
Maximum temperature of fumes °C	175	165	188			
Mean temp. of fumes °C	139	134	150			
Med. pressure indicated on water graduated tube -mm	1.4	1.5	1.5			
Gases average content of: Carbonic acid Vol%	6.8	7.2	7.2			
Carbon monoxide "	0.15	0.2	0.2			
Hydrogen "	0.05	0.01	0.01			
Coefficient of excess air	3	2.8	2.8			
Amount of heat imparted to water in:						
Pot 1 kcal	1,167	1,221	1,146	1,180	1,095	1,141
%	15.7	16.5	16.0	14.9	14.9	15.5
Pot 2 kcal	572	574	532	527	536	579
%	7.7	7.7	7.4	6.7	7.3	7.8
Pot 3 kcal	287	303	268	283	312	324
%	3.9	4.0	3.8	3.6	4.3	4.4
Total kcal	2,026	2,098	1,946	1,990	1,943	2,044
Yield for cooking %	27.2	28.2	27.2	25.2	26.5	27.7
Cooking time 1,2,3, in mins.	9,20,41	10,17,41	9,18,3[illegible]	11,19,38	10,18,36	11,18,36
Loss caused by:						
Unburnt wood %	2.0	2.0	2.0			
Registerable heat %	12.9	11.7	12.0			
Unburnt gases %	2.8	3.2	2.9			
Total loss %	17.7	16.9	18.9			
Technical yield of the combustion	82.3	83.1	81.1			
Heat given off by conduction and radiation	27.2	28.2	27.2			

Source: Singer (10)

were not well presented. Many of the recommendations for design modification ran counter to commonly accepted principles but no explanation was given.

Theodorovis[29] working in Egypt conducted tests to compare the efficiency of the traditional Egyptian stove with that of a traditional stove modified according to the principles of the Raju design. He measured the time required to heat a fixed quantity of water to the boiling point; the temperatures of the water at the different ports; and the fuel consumption. By using periodic temperature measurements he observed the heat retention characteristics of the stove.

While the methodology for measuring efficiency has become more standardized, there is still variation in experimental procedures. As the techniques become more consistent, the meaning of their results is being reexamined.

Since the amount of heat captured in the water depends on the physical characteristics of both the stove and the pot, Dutt[30] suggested that the efficiency measure be separated into a stove efficiency, ε_s and a pot efficiency, ε_p where the efficiency measured in the above experiments, ε_x, would be the product of these two factors. Although he worked out the equations for computing theoretical values of ε_p, no one has conducted the necessary experiments with different cooking vessels to determine a range of values for ε_p. Instead it has been held constant by using the same pot(s) for a series of experiments and obtaining the relative stove efficiencies where

$$\varepsilon_p = k \text{ (constant)}$$
$$\varepsilon_s = \varepsilon_x/k$$

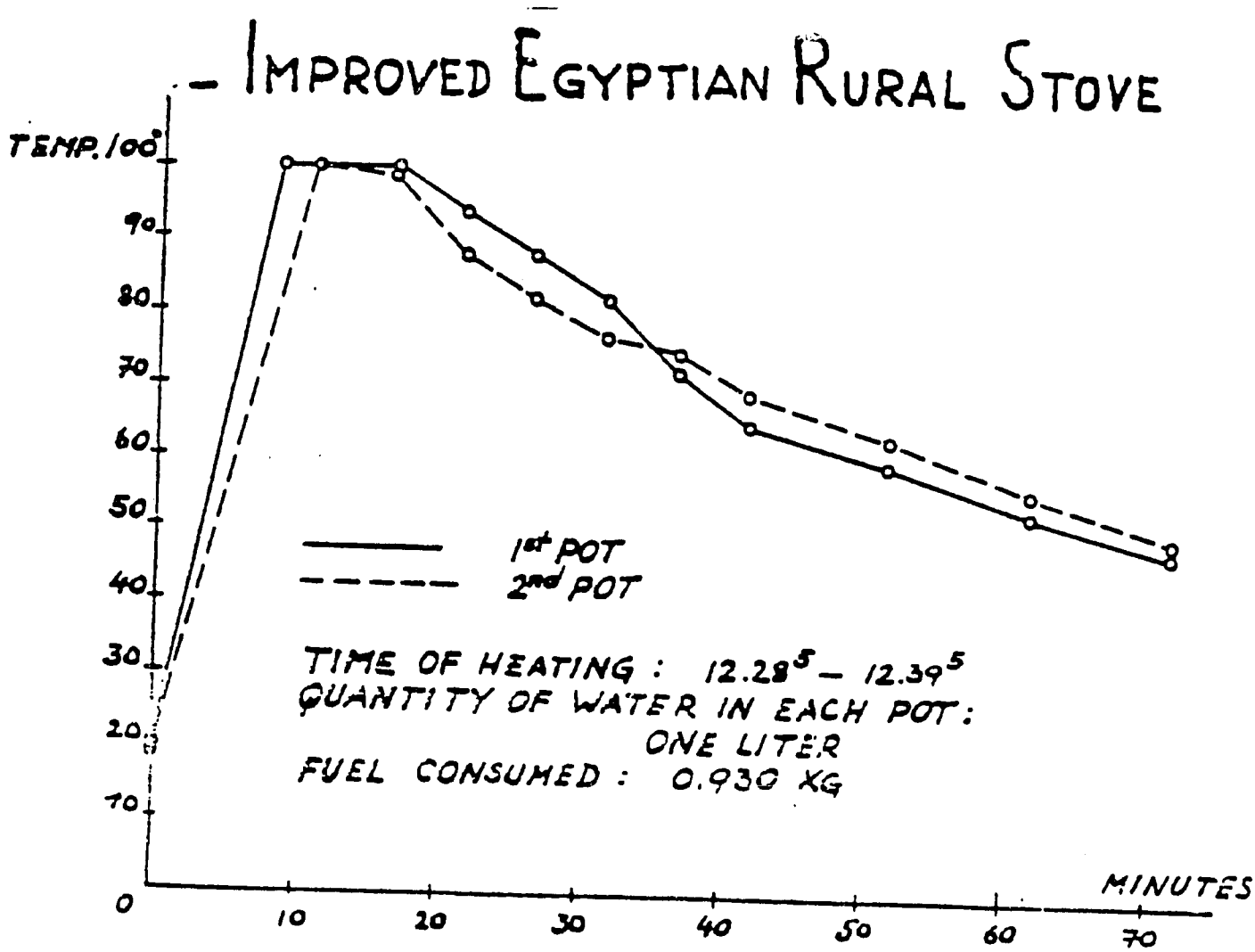
Stephen Joseph has observed that the experimental efficiency ε_x changes with different burning rates.[31] By varying the moisture content and shape of a specific fuel, he was able to vary its burning rate, which he measured by periodically weighing the fuel remaining in the stove. He found that at low burning

rates the experimental efficiency ε_x dropped off because heat losses through the pot and the stove wall were significant relative to the rate at which heat was generated. At high burning rates he found out that the experimental efficiency again dropped off but this time due to a limit on the rate at which the pot and its contents could absorb heat. The optimum efficiency was observed at a burning rate somewhere between these two. For some stoves the peak efficiency was quite sharp; for others there was a broad range of burning rates over which the experimental efficiency varied only slightly. In his most recent experimental work, soon to be published by ITDG, Joseph has measured the burning rate and held it constant when making comparisons between different stove designs. The effects of differences in burning rates can be included in the general efficiency equation as an efficiency factor, ε_f, relating to burning characteristics of the fuel. The resulting equation,

$$\varepsilon_f \varepsilon_p \varepsilon_s = \varepsilon_x$$

would take into account all three elements in the stove design process, the fuel, the cooking vessel and the stove.

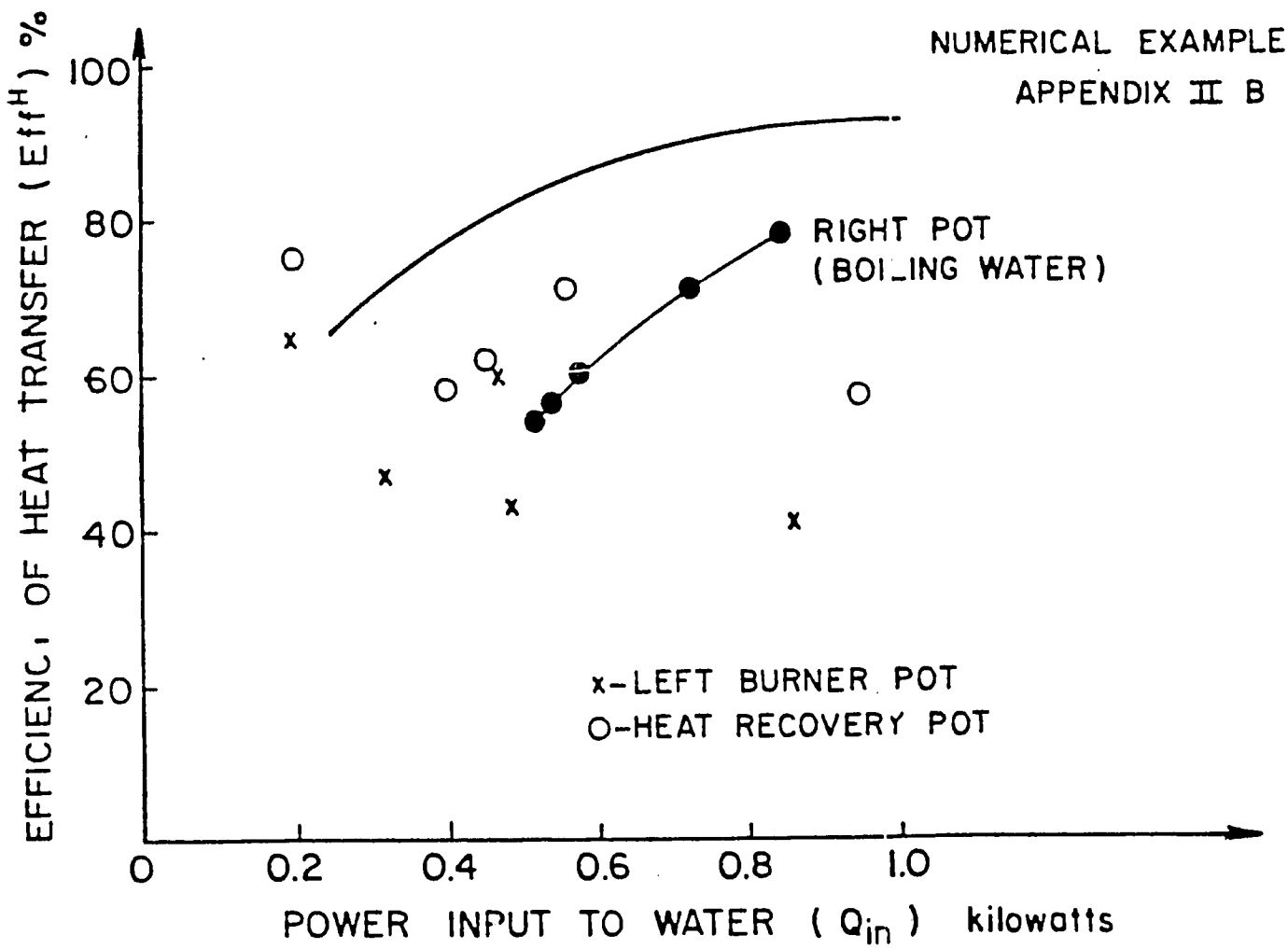
Most experimental work has been based on measurements made at the end of the experiment. Few attempts have been made to determine what is happening during the experiment. Periodic measurements of the rate of fuel consumption and the increase in water temperature would provide useful information about the performance of the stove under different cooking regimes, from quick frying to simmering overnight. The collection of this data requires more sophisticated, although readily available, equipment and more careful test procedures. Greater attention would be required to holding control variables constant, but the information obtained would considerably improve our understanding of what is happening in the different stoves.



Source: Theodorovis (34)

Figure 8

Loss of Heat Following Combustion



Source: Dutt (2)

Figure 9

Efficiency of Heat Transfer to Pot ($\mathcal{E}_p$) versus Rate of Heat Input

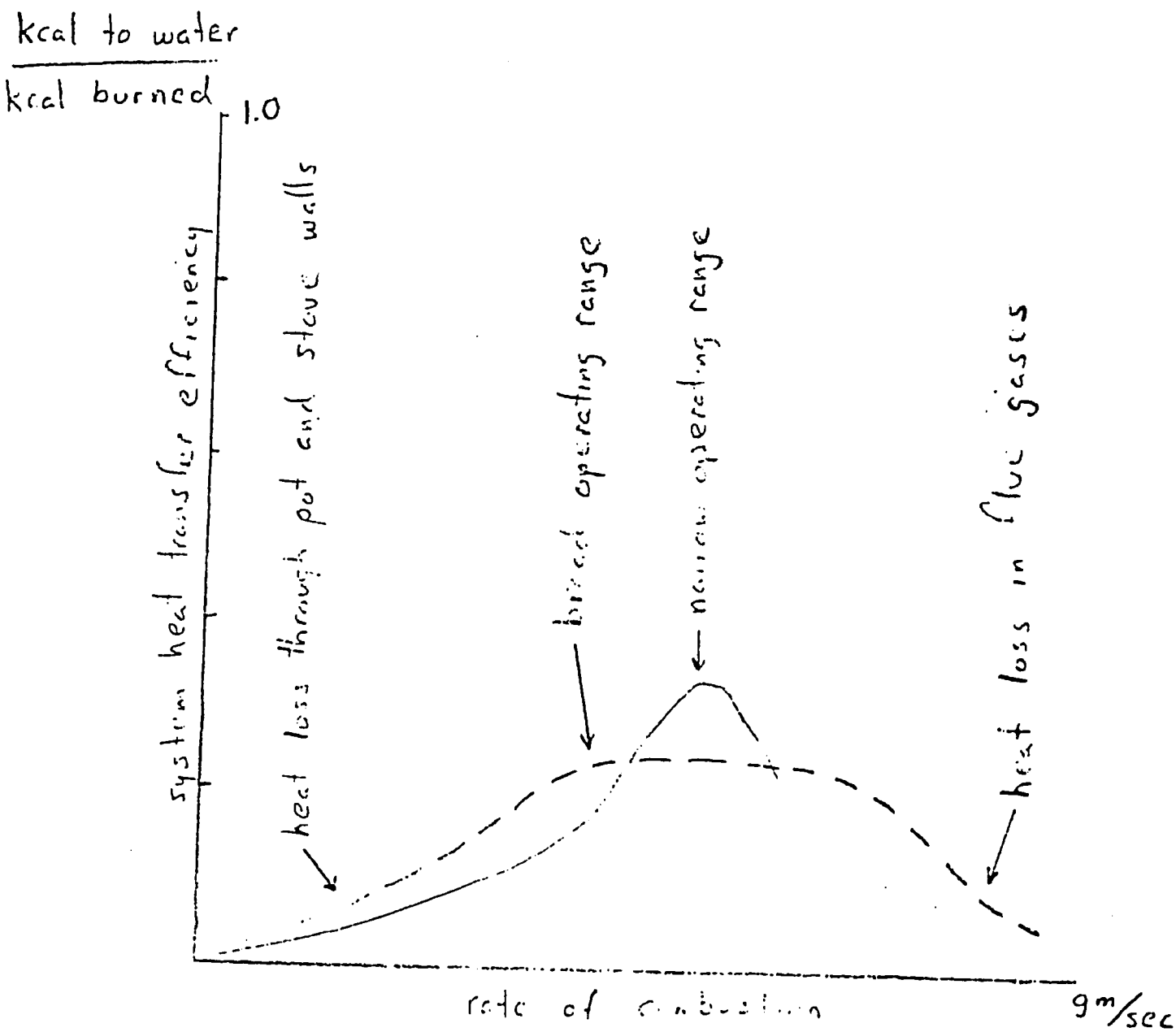


Figure 10

Hypothetical Curves - Rate of Combustion versus Heat Transfer Efficiency (ε_s)

VII. Stove Design Techniques

The development, testing, and dissemination of new or modified stove designs is a difficult and elaborate process which combines information from sociological surveys, engineering analysis, prototype designs, lab and field tests, and community participation. While the process is elaborate and time-consuming, it is commensurate with the current lack of knowledge about stove design and use. It is anticipated that as a body of knowledge is built up, the procedure can be simplified considerably. It is therefore very important that the information gathered during the early efforts be structured to maximize the knowledge about the total system of stoves, cooking, fuels, and cooking vessels. The following discussion describes a system of surveys, experiments and design procedures which is a synthesis of the ideas and practices of researchers involved in designing improved cooking stoves.

Basic research on stove design is not country-specific. It concerns the general thermodynamic properties of different stove designs. The research involves both physical experiments and engineering analysis. Currently the most important basic research is being directed by Stephen Joseph at ITDG's University of Reading laboratories. This project is analyzing a number of stove designs and materials to determine fuel consumption, stove durability, and operational difficulties. Four types of tests are being conducted; (1) the basic water boiling tests described in the previous section, (2) measurements of exhaust gases (to determine completeness of combustion), the time required to reach the charcoal combustion stage and the temperature of the stove walls, (3) user tests of the operational requirements for different designs, and (4) fuel consumption tests for cooking standard meals. This research has so far produced a number of interesting observations;

1. Under proper conditions (shielded from wind and carefully operated) the traditional three rock stove can obtain effi-

ciencies of 20% or more;

2. The rate of combustion of a fuel is a major factor affecting stove efficiency;

3. An increase in the residence time of the combustion gases in a heating chamber through a transverse flow pattern can increase the heat transferred;

4. The efficiency of a stove is very dependent on the attentiveness of the operator; where fuel is scarce cooks will achieve much higher stove efficiencies than in areas where adequate fuel supplies are available;

5. The measurement of efficiency for bringing a single pot to the boil has a high variance but over a longer test period the variance in efficiency measures decreases;

6. The measured efficiency drops as the test period extends into the period when the burning rate of the fuel drops off;

7. Specific definitions of efficiency are not so important as using a consistent test and providing sufficient backup data that other researchers can compute their own measures;

8. The temperature of the stove at the start of an experiment has an effect on the measure of efficiency; the hotter the stove, the higher the efficiency;

9. An effective stove design should not necessarily maximize efficiency but rather it should improve efficiency and reduce the variance in performance with changes in fuel characteristics and the attentiveness of the operator.

The basic research at Reading has produced two interesting procedures. First Joseph used the three rock traditional stove with its very simple combustion-heat transfer process as a base case with which other designs can be compared. Second he reduced many of the fuel related variables to a single variable, the rate of combustion.

The basic research on stove design and materials should include engineering analysis of heat transfer in the stove. The ITDG research is now being complemented by a thermodynamic analysis of the experimental data using both heat balance and heat transfer equations and assuming adiabatic conditions.

A general model of the heat transfer activities within a stove cannot be developed because of problems in modelling the fuel in terms of its rate of combustion and emissivity, the stove materials in terms of their thermal diffusivity, and the cooking vessel in terms of the temperature and velocity profiles of the gases flowing past the vessel. Specific models can be developed to analyze the transient heat transfer due to convection, conduction, and radiation at different locations within the stove. These models can then be calibrated with experimental data but their predictive value would be limited. They could not be used to determine the modifications that would maximize heat transfer to the cooking vessel, but they would indicate which changes might improve performance and which changes might lower performance.

The resulting mathematical models would serve two functions. First, they could be recalibrated for use with new designs. Second, they would identify the experimental data which should be collected and provide a format for the structuring of the data. The purpose of the basic research is to provide field workers with ideas on how to improve traditional and new stove design by modifying the dimensions of the combustion chamber, flue, and cooking ports, by selecting new materials for heat retention and insulation in the stove walls and cooking surface, and by adding new features such as a grate, chimney, or firedoor. Field research in contrast to basic research is more concerned with user requirements.

When undertaking a design project in a new country or area it is important that adequate data be collected on general fuel use, cooking habits, cuisine and methods,

social and cultural traditions relating to cooking, and existing stove designs. A cursory survey of village fuel use will establish the importance of cooking as a source of demand for local fuels and the potential savings to be realized if a more efficient stove can be introduced. A survey of cooking habits would tell what foods are cooked, how they are cooked, who cooks them, how frequently meals are cooked, how long meal preparation takes, and who gathers the fuel. Information on the social and cultural traditions associated with cooking must be collected with a participant observation survey in the target village. Information on the status relationships and social interactions associated with cooking would be collected and conclusions drawn as to the impacts of increasing or decreasing the time and attention spent on the cooking.

Existing stove models should be tested to determine their efficiency in transferring heat to one or more cooking vessels. A procedure for conducting such a test is detailed in Annex 1. The design relationships between the stoves, the cooking vessels and the fuels should be established and the rationale behind the evolution of these stove models should be identified. The analysis of existing models is very important because the criteria which led to the design of these stoves will probably apply to new designs and because the modification of existing designs is more likely to be accepted than the introduction of entirely new designs.

Once the background data has been collected then the actual design effort should begin. The most important factor is obtaining acceptance for a new stove design is local participation in the analysis, design, evaluation, and implementation activities of a stove design project. The target population should be involved, initially, as informants in the surveys, and, subsequently, as evaluators of the efficiency, usefulness, and ease of operation of new stove designs. Local technical

expertise should be employed in the assessment of existing stove models as well as in the design and evaluation of new stove models.

The development of prototype designs and modifications of existing stoves should be produced through an interaction between the village cooks and the stove designer. Community involvement can be fostered in a non-directive way by meeting with the villagers to raise the collective consciousness of energy problems and to encourage these residents to articulate their needs. Once an awareness of the need for new stoves had been established the designer would be brought in to interact with the community. Alternatively, the community can be involved in the stove design process in a directed way by selecting villagers for participation in the testing and evaluation of different designs. The possible modes of community participation have been discussed by Elmendorf[32].

The actual design work should take place in the target village to the maximum extent possible. While it may not be possible to set up a rural testing facility to measure heat transfer characteristics, it is essential to conduct the operational and cooking studies tests in the village.

If the community is actively involved in the testing and evaluation of different prototypes, then the dissemination of the design which satisfies the perceived needs of the villagers should be easy. However the dissemination of the prototype beyond the test village will be more difficult. The four mechanisms for dissemination of stove innovations are; (1) for easily fabricated models - through village opinion leaders, (2) for more complex models - through distribution of models and publications, and training of rural artisans in the methods of construction, (3) for commercially fabricated models - through the private market, and (4) for all models - through rural extension services. Where artisans are trained in constructing the prototypes it may be necessary to permit entrepreneurs to modify the design to suit local conditions.

While the success of a dissemination effort depends on a number of factors, it is worth pointing out some situations in which the probability of success would be high. If the design improvement were an industrially fabricated item such as a cooking pot and if the modification involved little increase in production costs but clear advantages to the rural cook, then the private market would make these available to attract replacement orders as well as new orders. If the design improvement were a simple modification to an existing design, such as a ceramic grate, and if it could be locally manufactured at a cost below that of the stove, then demand should be forthcoming. If a new stove model were to reduce the labor needed for cooking or preparing food as well as to consume less fuel and if it were not significantly harder to construct, then the dissemination through community leaders or opinion leaders should be successful.

VIII. Policies

The testing, design, and dissemination of cooking stoves in rural areas has been receiving increasing attention over the last three years. As this interest grows, it is important to focus on the goals of these efforts and to maintain the quality of the work being done. The goal of stove design is to develop stove models which rural populations will adopt in preference to their traditional stoves and which will reduce the consumption stove models which will be adopted in preference to traditional stoves and which will reduce the consumption of fuel required for normal cooking. The quality of past stove work has been uneven. For testing few have matched the care and thoroughness of Singer[33] and Joseph[34]. In design very few breakthroughs have been made since Raju's smokeless chula although several interesting modifications have been tried. For dissemination, only the Choqui experience has come anywhere close to being effective.[35]

There appear to be five areas of stove design in which the USDA and USAID could effectively participate; applied research, user surveys, field research, dissemination of research and survey findings, and analysis of cooking systems. Applied research into the processes of combustion and heat transfer in rural cooking stoves is an area which can be undertaken by University researchers, provided they liaison with researchers and field workers in LDC's who can articulate the operational problems and provide information on the types of fuel, cooking vessels, and stove models which are currently being used.

The work of ITDG at Reading provides an excellent example. Stephen Joseph combines a familiarity with LDC problems and a good technical background. Aside from ITDG, others working in this field are; the Department of Applied Physics and Mechanical Engineering at Technische Hogeschool Eindhoven, and the Center for Environmental Studies at Princeton University. The applied research utilizes physical and mathematical models to test the interactions between the selection and preparation of the fuels and the design of the combustion chamber and between the configuration of the flue and the design and location of the cooking vessels. Disciplines which would be useful in this research include combustion, fluid dynamics, heat transfer, materials, and structures.

The survey of cooking fuel use in rural areas has become increasingly sophisticated over the last five years and more attention has been paid to user needs and choices. However the actual cooking activity is only beginning to be explored. The most thorough effort in looking at how stoves are used was conducted in Guatemala by researchers at the Choqui Experimental Station and by Dale Schaller.[36] Studies of this type require extensive field work and should precede to the field research on stove testing and design. The role of women researchers in this effort and in the subsequent field testing should be stressed.

Disciplines which would be helpful in these surveys are anthropology and sociology, but of particular importance is experience in living in rural villages.

Field research includes the testing, modification and design of cooking stoves at the village level. This effort requires an integration of physical and practical tests, innovative design and community participation. This activity is now underway in a number of countries, under the guidance of Institute Technology Bandung (DTC) in Indonesia, Volunteers in Asia and Dian Desa in Indonesia, Appropriate Technology Development Association in Lucknow, India, the University of Dar Es Salaam in Tanzania, the Choqui Experimental Station in Guatemala, the Forestry Department in Nepal, VITA, ITDG, and SRAT (Voltaic) in Upper Volta, the Aprovecho Institute in Senegal, the CILSS in the Sahel, the Institute of Science and Technology in Bangladesh, the University of Ibadan in Nigeria, the Industrial Development Board in Sri Lanka, the University of the Phillippines at Los Banos, and the National Energy Administration in Thailand, among others.

The history of previous efforts provides better information on the difficulties than on the successes. The major problems have been insufficient time in the field, inadequate interaction with the potential users and understanding of their needs, insufficient knowledge of the physics of stoves, inaccurate and unenlightening testing procedures, and lack of commitment for a follow-on effort. The goal of field research is to develop a design which is appropriate to the perceived needs of the user. For this research a variety of disciplines are useful but the primary requirements are for experienced and empathetic field workers and innovative designers.

The selection of projects should maximize the knowledge obtained. The user needs will be different for areas which are suffering an acute scarcity of renewable fuels and areas which have an adequate but diminishing supply of fuels. The stove performance requirements will be different for areas which do quick cooking and areas which do simmering or slow

stewing. The design problems will differ for areas which use ceramic or metal pots, burn wood, agricultural wastes, charcoal or dung, cook indoors, in a shelter, or outdoors, and have more or less sophisticated traditional stove designs.

The dissemination of new stove designs to the rural populace is a problem for local extension services and volunteer agencies. While the USDA and USAID could involve themselves in the funding of such dissemination activities, they could also assist in the dissemination of ideas and technologies to researchers in the LDC's. Since much of the work in stove design is presented in the form of memos, research reports and articles, it is difficult to obtain information on current activities. VITA has attempted to act as a clearinghouse through its distribution of a package of stove articles and through its upcoming publication, The Design of Wood Conserving Stoves. FAO has contracted for a state-of-the-art report to be published later this year.

Although much is being written, little effort has been made to assess the quality of the reports, and to categorize them according to the activities undertaken and the type of stoves considered. A well organized library activity with up-to-date information on what research is being undertaken, copies of the research reports that are produced, and a network of addresses for searching out new information and disseminating what is acquired would provide a valuable service.

This report like others before it has attempted to identify the design elements of cooking stoves, specifically the physical features and processes. These elements are usually described as components of a system but treated as separate entities by researchers. The type of fuel used in a stove and the preparation of that fuel prior to combustion will affect the performance of the stove. No consideration has been given to relating this information to planning for the supply and processing of community woodlots or biomass plant-

ations. The type and number of cooking vessels used will affect the amount of heat transferred from the burning fuel to the food. Rural families have demonstrated their willingness to adopt new vessels such as aluminum pots where they provide distinct advantages over the older cooking vessels, however no attempt has been made to redesign these pots to be suitable for the improved stove designs. Systems analysis, where it is not bogged down in computer programs or elaborate flow charts, can provide a framework for the economic and technical analysis necessary to interrelate the various components involved in cooking and to identify where the most effective improvements can be realized. This type of analysis is worthwhile only when good input data is provided. It would be useful to structure the results of the various research efforts into such a framework and to evaluate funding and policy alternatives to determine the more efficient use of natural resources.

IX. Report Abstracts

REDUCING COOKING ENERGY USE IN RURAL INDIA

G.S. DUTT

This report describes some work performed by Dutt at the Ungra extension center of ASTRA. Using both theory and experimentation he explored the effect of heat losses through the cooking vessel and its contents on the net transfer of heat to the cooking vessel. From this work he was able to derive an estimate of the pot transfer efficiency, ξ_p, which could then be combined with the stove efficiency, ξ_s, to determine the total efficiency of heat transfer from the burning fuel to the contents of the cooking vessel.

Dutt's work represents the type of applied research that is required to improve our knowledge about how to design more fuel efficient stoves. His ability to combine the theory of heat transfer with an understanding of rural cooking requirements produced very exciting results. Perhaps for the first time a formal attempt has been made to explore the interface between the stove and the cooking vessel, with particular attention being paid to the position and configuration of the vessel.

EFFICIENT WOOD BURNING COOKING STOVE LITERATURE

G.S. DUTT

This report reviews the literature on stoves which have been tested, specifically the work of Singer, the National Building Organization (India), and Theodorovis. The author points out that there is no *a priori* advantage to stoves equipped with chimneys. While a chimney carries the smoke away from the cooking area, it also carries away hot gases which might otherwise be used to heat the cooking vessel. Finding that the available literature does not deal with this issue in a rigorous manner, Dutt attempted some experiments of his own only to discover that the results of boiling water tests can be highly variable even when attempts are made to standardize the fuel. This finding is consistent with Stephen Joseph's experience even though he used tighter standards on the type of fuel, the cooking vessel and the starting temperature of the stove. Dutt concluded that a sufficient number of tests must be made in order to reduce this variance.

Dutt went on to discuss the various experimental results from previous stove tests. He attempted to explain some of the inconsistencies in the results by speculating what variables had not been controlled. Again Dutt's scientific training is evident in his ability to separate out the meaningful from the meaningless.

LORENA OWNER-BUILT STOVES

IANTO EVANS

This is one of many publications which describe the Lorena stove developed by Ianto Evans and Donald Wharton while they were working at the Choqui Experimental Station in Guatemala. The book provides step-by-step instructions for constructing and operating the Lorena Stove. Special emphasis is placed on the preparation of the sand and mud mixture. The stove design described in this book has a high thermal mass as required for slow simmering of beans and for providing space heating as well as cooking heat. The author has gone on to design additional versions of this model, some with less thermal mass. However, strength of the materials in the stove requires that the walls have a minimum thickness which is much wider than a ceramic stove. While repeated claims have been made for the considerable savings in fuel attendant with the introduction of this unit, there is no published information on any testing that has been done.

Efforts are now underway in a half dozen or more countries to introduce variants of the Lorena stove. While the construction of the Lorena has evolved from a specific model to a process in which many configurations can be tried, it remains a high thermal mass unit which requires a craftsman for construction and sand and mud mixtures for the walls. The attempt to universally apply a given design begs the question of what the needs of the users are. Still this unit is the first design since the Hyderabad Chula to receive such widespread dissemination.

IMPROVED COOKSTOVES FOR RURAL SENEGAL

IANTO EVANS, ELISABETH GERN AND LAURENCE JACOBS

This report provides a summary of a 5 week consulting mission to Senegal. As the authors point out in the beginning of their report, the tasks set out were immense. Despite this they claim to have made a start at four tasks; 1) prepare a socio-cultural assessment of needs and constraints, 2) develop with villagers a basic system for building stoves, 3) work with the local agency to develop a training and testing system, 4) propose a mechanism for promotion and dissemination.

The consultants constructed over 20 prototypes before the mission ended, however all of these were modifications of the Lorena stove designed for one or two cooking ports.

The consultants had some interaction with the target population and later modifications took into account the concerns of the villagers, but they relied very heavily on their experience in Guatemala and Honduras. Quick assessments were made of traditional stoves, fuels, cooking vessels, and cooking habits and locations, but the emphasis was on getting prototypes constructed and planning for a stove testing facility.

The approach of this project is very much one of selling a specific product. Although the consultants are aware of the weakness of this approach, they had no alternative given the time constraints of the project. The project will provide a very visible demonstration project, but it is unlikely to have any long term effect on the use of cooking stoves in Senegal unless the local craftsmen borrow certain features of the Lorena stove for use on their traditional models.

COOKING STOVES - THE STATE OF THE ART

R.I. BROWN

This report examines the reported efficiencies of various cooking stoves. It then discusses methods for improving stove efficiency and providing extension services to disseminate new designs. A comparison is made between traditional cooking stoves efficiencies and those for electric and gas stoves. The relevance of this comparison is not evident. The report is based on the available literature and is not very thorough in its treatment of different designs. It provides calculations showing the theoretical change in radiant heat capture as the distance from the flame increases, but there is no supporting experimental work. The report concludes with recommendations for World Bank support of the introduction of new stove designs.

DESIGNING STOVES FOR THIRD WORLD COUNTRIES

HELEN GOULD, STEPHEN JOSEPH

This short report discusses socio-cultural factors in stove design. These factors can be observed in the methods of food preparation and cooking, the evolution of traditional cooking devices, and the general attitudes towards innovations. Sex, status, and kinship roles affect the cooking and fuel collection activities, and therefore the stove requirements. The aut ors argue that the stove designer must be familiar with this information if he is to develop an appropriate design.

SOME CONSIDERATIONS PERTAINING TO THE PROBLEM OF WOOD-BURNING

A.M. KANURY, P.L. BLACKSHEAR, JR.

This article explores all aspects of wood combustion including the movement of the layer of pyrolysis, the diffusion of condensable vapors within the wood, the thermal diffusivity of wood, and the physical properties of charred wood. The analysis provides insights into the changes in mass burning rate with different size pieces of wood and with the movement of the pyrolysis layer. The heat losses due to convection flows of gases out of the wood reduce the rate at which conduction raises the interior temperature of burning wood.

This article provides a better understanding of the wood burning process. Their model can be used to interpret the experimental data on the mass burning rates of fuel in a wood cooking stove, and to improve the design of the combustion chamber.

IMPROVEMENTS OF FIREPLACES FOR DOMESTIC USE OF FIREWOOD: ITS POTENTIAL AND IMPACT ON THE SAHEL

J. KI-ZERBO, G. de LEPELEIRE

This report discusses a consulting trip to Niger and Upper Volta to determine the need for improved cooking stoves in the Sahel. The authors examined the traditional cooking vessels, stoves, and fuels, and the current level of demand for cooking fuel. The social aspects of the cooking fuel collection activities are described. Finally, the current stove design efforts are reviewed to determine whether or not they are successful, and a proposal for a more thorough stove design effort is included.

Although their examination of the stove design issues in the Sahel is rather cursory, it derives from a sound methodology. The consulting team combined technical and sociological skills. Ms. Ki-Zerbo identified the role of women in structuring the cooking and fuel collection activity and Prof. de Lepeleire examined the stove technologies. The project proposal stresses the use of women coordinators in the study and research phase. As a first step towards a stove design project, this report is well directed.

A STUDY ON THE EFFICIENCY OF CHULAHS

NATIONAL BUILDING ORGANIZATION (INDIA)

This report presents the results of a series of experiments. The first involved measuring the relative efficiencies of a number of stoves using the standard boiling water tests. The two most efficient designs were then tested to determine the impact of changing the dimensions of the cooking ports and chimney and the distances between the chimney and cooking ports. Finally a single model was chosen to test the effects on efficiency of changes in the shape of the cooking vessel and chimney, the insulation in the combustion chamber, the slope of the flue. the clearance between the cooking vessel and port, and the color of the cooking vessel.

The presentation of the test results was most unsatisfactory. The data on the type of fuel and cooking vessels used was insufficient. Where test results appeared illogical, no attempt was made to explain the apparent inconsistencies. Perhaps most annoying was the use of boiling tests to measure very specific physical properties. Continuous measures of the water temperature and a closer attention to the effects of fuel selection and preparation would have increased the credibility of this report. This report provides a good counterpoint to the excellent work done by Singer.

A COMPARISON OF METAL AND CLAY CHARCOAL COOKING STOVES

KEITH OPENSHAW

This report describes the charcoal stove design traditionally used in Tanzania and an alternative design currently used in Thailand. It provides a brief description of the materials and design of each and then presents the result from some boiling water experiments. Based on these experiments the author estimates the potential fuel savings to the country if the Thai stove were used in place of the traditional stove. No plan is divised for the dissemination of the new model.

This brief report provides a good summary of a comparative stove test. Before any judgement can be made as to the overall advantage of one design relative to the other, further tests have to be carried out to determine the relative fuel consumption during actual cooking and to identify the additional operating difficulties and costs associated with the Thai model. The author did not perform any preliminary surveys of potential target populations, but his experience in Tanzania as a forester and professor provided him with an understanding of local conditions. It remains to be seen if the new design will be picked up by local artisans and marketed in place of the traditional stove.

SMOKELESS KITCHENS FOR THE MILLIONS

S.P. RAJU

This report describes the first and perhaps most revolutionary of the post-war attempts at stove design. The Hyderabad Chula represents a major change from the traditional designs. It removed the smoke from the kitchen, improved the draft in the stove, and protected the cook from excessive heat. This report provides detailed instructions on the construction of the chula as well as a discussion of its virtues.

Despite the attempts to spread this design to other areas beginning in 1946, the chula is not widely used today. The original design has been modified over the decades in an attempt to meet local needs but successes have been lacking. A great idea but not adopted; why? This is the problem that confronts modern stove designers.

Raju, in designing this chula, was motivated by his perceptions of the drudgery and health hazards associated with the traditional Indian cooking activity. However his solution was a relatively sophisticated design which required a craftsman to construct. Clearly the design was evolved with an understanding of rural cooking but probably without the participation of rural cooks. It is hard to judge what other constraints to adoption existed. No follow up studies are known. The lack of acceptance of this design has led to the more involved procedure for stove design described in works by Joseph, De Lepeire and in the accompanying report.

THERMAL ANALYSIS OF FOREST FUELS

F. SHAFIZADEH, W. DE GROOT

This article describes the use of thermal analysis for measuring the sequence of reactions during pyrolysis and the energy and mass transformations which occur as the fuel substrate is heated. The techniques applied include thermogravimetry, and thermal evolution analysis. The former provides a continuous measure of the loss in weight as a function of temperature or time. The latter provides information on the temperature at which volatile degradation products are produced. Together these techniques provide the data necessary to characterize the material and energy balances during pyrolysis and combustion. With this information an evaluation of different bio-mass fuels can be made and their thermal conversion processes can be accurately described. This analysis would provide better understanding of the relation between fuel selection and combustion in wood stoves.

THE WOODBURNERS ENCYCLOPEDIA

JAY SHELTON

This publication is the classic in its field. It discusses all aspects of wood heating stoves, and in the process covers most of the basics regarding combustion, heat transfer and efficiency. It summarizes much of the previous work done on wood combustion including information on the sequence of pyrolysis in wood, the rate of combustion, and the transition from flame combustion to glowing combustion. While the author's own experiments dealt with airtight stoves for space heating, his analysis of stove efficiencies is relevant to cooking stoves. His discussion of chimneys and chimney fires is applicable to smokeless cookstoves. He points out the various design trade-offs such as completeness of combustion versus maximizing heat transfer, and the use of primary versus secondary air. This book provides an excellent technical background for the stove designer.

IMPROVEMENT OF FUELWOOD COOKING STOVES AND ECONOMY IN FUELWOOD CONSUMPTION

H. SINGER

This FAO report describes a stove testing and design project in Indonesia in 1960. This report set the standard for stove testing. Singer used chemical analysis of the flue gases to determine the completeness of combustion, boiling water experiments to obtain relative efficiency measures and cooking tests to determine potential savings in fuel consumption. While Singer was testing a number of local stove designs, he developed a number of new designs based largely on the concepts introduced by Raju ten years earlier.

Technically this report is outstanding and it established the standards for stove testing. However the work was conducted at a University Laboratory and was not followed by a field research program. As a result the Singer design was never adopted by rural Indonesians. The author anticipated that dissemination of the design would be accomplished through the commercial market, but his assignment ended before he could modify the construction requirements to be suitable for domestic use. The project may have been viable and implementable but there was no time to prove it.

A DESIGN GUIDE FOR WOOD CONSERVING STOVES*

VITA/ITDG

This compendium incorporates much of the earlier work of Stephen Joseph. This report and Joseph's state-of-the-art paper for FAO will complete the Stove Quartet which includes the works of Singer and Raju. The report begins by discussing the mechanism of combustion and heat transfer and goes on to examine a number of traditional designs including the three rock stove, the chula and the sawdust and charcoal burning stoves. Next the techniques for improving stove efficiency are reviewed and a number of improved designs with and without chimneys are presented. Finally the report describes the methodologies for testing stoves and for organizing a stove design program.

The author is one of the leading researchers on cooking stove design. This report contains many of the insights he has acquired from his extensive travels and research. This report does not contain experimental data on the different stove designs. Future publication by ITDG will catalogue the results of the experiments conducted at the Reading facility.

*This report is only available in draft form and therefore is not included. It will be available from VITA in the autumn of 1980.

DESIGN OF WOODBURNING STOVES/OVENS

VITA DOCUMENTATION SERVICE (VARIOUS AUTHORS)

This is a collection of 24 reprints of articles on stove design.* Most of the articles present a description of the design but very little experimental information on the efficiency of the stove. The designs which are presented generally use secondary fuels such as sawdust or rice husks. or consist of a variation on the Hyderabad chula. The articles are generally written by the designer and offer very little information on the needs of the potential users or the means for dissemination. The result is a collection of design options but with very little insight into the stove design procedure.

*This series is not included in the attached reports but can be obtained from the VITA documentation Center, 3706 Rhode Island Avenue, Mt. Ranier, Maryland 20822.

Footnotes

1. The author's own study in Indonesia, Ernst's study in Upper Volta, and
2. Both reports should be available in late 1980; the former from VITA in Washington (Paula Gubbins) and the latter from FAO in Rome (M.R. DeMontalembert)
3. The author has been greatly aided in this by discussions with Stephen Joseph at ITDG, Guatam Dutt at Princeton, and John Tatam at ITB, Bandung.
4. The term efficiency as used throughout the report refers to a measurement of the heat captured in the food or water being heated and the chemical energy content of the fuel which is released through combustion.
5. Openshaw (32)
6. Gould and Joseph (6), Evans (41), Elmendorf (4), Schaller (8)
7. Gould and Joseph (6)
8. Raju (7), Singer (10), Evans (40)
9. Kalluppatti (46)
10. Tata Research Institute (India) (33)
11. VITA/ITDG (11)
12. Ibid
13. Openshaw (32)
14. Ki-Zerbo (25)
15. Singer (10), NBOI (31), Georgia Tech (43), Chanco (37), Darrow (38)
16. Dutt (2)
17. NBOI (31), Dutt (2), Goldemberg (15)
18. Dutt (2)
19. Shelton (9)
20. Shelton (9), VITA/ITDG (11), Kanury (17), Browne (13)
21. Stephen Joseph, personal communication
22. Dutt (2)

23. Shafizadeh (21)
24. Oven-dry wood, Shelton (9)
25. Metz (18)
26. In this and subsequent sections the term flue refers to the channel through which heated gases pass. It extends from the combustion chamber to the exhaust port. The exhaust port includes the chimney.
27. Singer (10)
28. BNOI (31)
29. Theodorovis (34)
30. Dutt (2)
31. Stephen Joseph, personal communication.
32. Elmendorf (4)
33. Singer (10)
34. Joseph (23)
35. Evans (40), Schaller (8)
36. Schaller (8)

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Annex 1

Stove Testing Procedure - Existing Designs

1. Examine stove for faults
2. Note local cooking procedures
3. Measure the stove and draw a layout, with dimensions of the walls and cooking ports, the combustion chamber, and the fuel loading port
4. Note the type of materials used, the cost and age of the stove, and whether it has been in continual use
5. Measure the dimensions and weight of the cooking vessels.
6. Fill the vessels with the specified quantity of water
7. Record the ambient temperature of the water, the surrounding air, the stove walls inside and out and near each cook port
8. Note if the cooking area has a draft due to windy conditions
9. Weigh the fuel wood after setting aside about 200 gm. for measuring the moisture content
10. Decide on where vessels are to be placed, cover the unused cooking ports
11. Decide on a standard fuel ignition procedure
12. Record the starting time for ignition
13. Measure the water temperature every 2nd minute, the stack temperature and the CO_2 concentration every 3rd minute
14. Measure the time required to bring the water in each vessel to a boil
15. Extinguish the fuel after a specified period of time
16. Remove the fuel from the stove and knock off the charcoal
17. Weigh the wood and the charcoal separately
18. Measure the volume of water in each cooking vessel
19. Measure the temperature of the stove walls inside, outside, and around the cooking ports

Stove Design and Testing Data Sheets *

Stove characteristics

1. General information

1.1 Origin

a) Country .....

b) Region .....

c) Organisation .....

d) Designer .....

1.2 Date of construction .....

2. Design information

2.1 What type of fuel can the stove burn?

a) Charcoal Yes/No*

b) Wood Yes/No

c) Rice husks Yes/No

d/ Straw Yes/No

e) Others .....

2.2 Can the stove be used for:

a) Domestic cooking Yes/No

b) Space heating Yes/No

c) Food processing (specify e.g. smoking) Yes/No

d) Water heating Yes/No

e) Baking Yes/No

f) Other .....

* Source: VITA/ITDG (11)

2.3 Construction by:

a) Artisan Yes/No

b) Stove owner Yes/No

c) Small rural industry Yes/No

2.4 Constructi[illegible] time (man hours)

a) Time needed for skilled labour .....

b) Time needed for unskilled labour .....

c) Time needed for owner's labour .....

Note: Give other information on method of construction and resources needed.

2.5. Cost (in currency of country) .....

2.6. Estimated lifetime (years) .....

A. a) Have these stoves been used continuously? Yes/No

b) For how long? ..... months

c) By whom? .....

B. a) Have these stoves been tested in a workshop? Yes/No

b) For how long? ..... hours

c) Over what period of time? ..... months

2.7 Maintenance requirements

Recommended interval between cleaning of flue (months) .....

Recommended interval between replacement of flue (months) .....

Recommended interval between replacement or repair of main body (months) .....

2.8 Safety:

a) Liable to catch fire if not cleaned Yes/No

b) Possibility of ash or coals entering room Yes/No

c) Others (specify) .....

2.9 Materials requirement

	Weight	Cost	Materials Local	Materials Imported
a) Mud (sand and clay)				
b) Mud + additives				
c) Clay bricks (sun-dried)				
d) Clay bricks (fired)				
e) Ceramic				
f) Ceramic + additives				
g) Portland cement				
h) Refractory cement				
i) Crushed fire-clay/cement				
j) Steel sheet (gauge .....)				
k) Steel plate (thickness .....mm)				
l) Cast iron				
m) Other (specify)				

2.10 Overall dimensions

a) Length ..... cm

b) Width ..... cm

c) Depth (or height from ground ..... cm

d) Attach sketches

2.11 Cooking practices

Specify local food that is cooked and method of preparation.

3. Detailed design information

3.1 Number of holes for pots .....

3.2 Are these holes designed to accommodate:

a) Flat bottomed pots Yes/No

b) Round bottomed pots Yes/No

3.3 Can the pots be inserted in flue gas stream? Yes/No*

How far do they sit inside? ..... cm.

3.4 Oven included Yes/No

Inside dimensions: Length ..... cm. Width ..... cm.

Depth ..... cm.

3.5 Hot water boiler Yes/No

Inside dimensions: Length ..... cm. Width ..... cm.

Depth ..... cm.

3.6 Chimney

a) Materials .....

b) Height .....cm. Diameter inside ..... cm.

c) Damper Yes/No

d) Rain arrestor Yes/No

3.7 Primary air control Yes/No

3.8 Secondary air control Yes/No

3.9 Hearth size: Length ..... cm. Width .....cm. Depth .....

3.10 Hearth door Yes/No

Size: Length ..... cm. Width ..... cm.

3.11 Grate Yes/No

Size: Length ..... cm. Width ..... cm.

3.12 Type of air flow through the combustion chamber:

a) Downdraught Yes/No
b) Updraught Yes/No
c) Cross draught Yes/No
d) Diagonal draught Yes/No
e) S-draught Yes/No

3.13 Baffles Yes/No

Number Materials .....

* delete as applicable

4. Cooking and combustion test data sheet

4.1 Stove (name) .....

Model no. .....

Local name .....

Experimenters .....

4.2 Fuel:

a) Scientific name .....

b) Local name .....

c) Calorific value .....

d) Moisture content ..... per cent

e) Length of wood ..... cm.

f) Cross section area .....cm.

4.3 Kindling

a) Scientific name .....

b) Local name .....

c) Calorific value .....

d) Moisture content ..... per cent

e) Form: Twigs ..... Splinters .....

Waste ..... Other .....

4.4 Cooking vessels

a) Type .....

b) Material .....

c) Specific heat .....

d) Number used in test .....

e) Dimensions of individual containers:

Diameter ..... cm Depth ..... mm Wall thickness ..... mm

Diameter ..... cm Depth ..... mm Wall thickness ..... mm

Diameter ..... cm Depth ..... mm Wall thickness ..... mm

f) Were [illegible]s on Pot 1 Yes/N[illegible]

Pot 2 Yes/No

Pot 3 Yes/No

4.5 Test medium:

a) Water (weight) ..... gms

b) Oil (weight) ..... gms

c) Food (list components and their weights) for each pot,

e.g. Pot 1 Food : Rice weight .....gms

Water weight .....gms

d) Method of preparation: describe in detail (should mirror local practice).

5. Experimental data - Run schedule

5.1 Firewood:

a) Weight at start ..... gms

b) Weight of unused fuel ..... gms

c) Weight of unburnt charcoal ..... gms

d) Weight of unburnt wood ..... gms

e) Weight of ash ..... gms

5.2 Feed rate:

Continuous / intermittent / single charge

Comments:

(e.g. How often was wood loaded if the feed rate was intermittent and how many kilograms/hour were burnt?)

5.3 Containers:

	No. 1	No. 2	No. 3
a) Container weight	gms	gms	
b) Weight of test medium	gms	gms	
c) Container + test medium at start	gms	gms	

	No. 1	No. 2	No. 3
d) Container + test medium at finish	gms	gms	
e) Weight loss	gms	gms	

f) Which containers have lids?

B. Specify:

a) Number of containers used .....

b) Number of ports that are not covered with pots .....

c) Number of ports that are not covered with pots but are covered with a lid .....

5.4 Ambient conditions:

A. Ambient temperature

a) Test medium Pot No. 1 .....°C Pot No. 2.....°C Pot no.3...

b) Air inside cook house .....°C

c) Air outside cook house .....°C

B. Wind velocity

a) Outside enclosure m/sec

b) Inside enclosure m/sec

C. Air pressure ..... (this can be signified by height above sea level)

6. Additional tests

6.1 Other useful measurements that help calculate heat transfer in the stove are:

a) Initial temperature of stove wall inside and outside (in the combustion chamber and flue).

Final temperature of stove walls inside and outside (in the combustion chamber and flue).

Before and after measurements should be taken in the same place and should be distributed around the outside and inside surfaces of the stove.

b) Velocity of flue gases .....m/sec (as a function of time).

c) Measurements can also be taken of the heat loss from the pots and stove after the wood has been burnt (i.e. readings are taken at a fixed intervals until the stove and pots reach room temperature).

d) Others .....

6.2 Comments:

a) Other columns would be added if any further measurements are to be taken.

b) The position of primary and secondary air controllers and the dampers can be indicated by specifying the percentage of the total area of the controller open to gas flow (e.g. fully open, three-quarters open closed).

1. Test run data: Example

Stove: Model No. Experiment No.

	Temperature °C				Gas Analysis			Air Control			Smoke	
Time/mins	Pot No.1	Pot No.2	Pot No.3	Stack	CO%	CO_2%	O_2%	Prim.	Sec.	Dampers..	Notes	Comments
10	40	30	10	150	.05	6	11	Fully open	Closed	Open	Some grey smoke	
20	70	40	30	180	.04	7	12	Quarter open	Closed	Half open	None	

:. User Survey (Possible questions and layout)

General

Household No.....

Person	Age	Occupation	Income	Whether interviewed

1. Are you very/fairly/not satisfied with your stove?
2. What are its main benefits? (in order of priority)

   .....

   .....
3. Do you now use less/same/more firewood?
4. Do you spend more/same/less a) time collecting firewood?

   more/same/less b) money purchasing wood?
5. Is less/same/more effort required for cooking?
6. Is your stove safer than an open fire? Yes/No

   Why? .....
7. Do you still use an open fire? Yes/No. If so, how often?.....

   Why? .....
8. What are the main disadvantages of your stove?

   .....

   .....
9. Has the stove changed:

   a) How you prepare food? Yes/No How? .....

   b) How you cook? Yes/No. How? .....

   c) When and where you eat? Yes/No. How? .....

d) Your daily work routine? Yes/No. How? .....

e) General comments .....
.....

Specific design questions

10. Does the stove have enough/too much/too few cooking ports?

11. How often do you use all the ports? Frequently/sometimes/rarely.

12. Do you cover unused ports when cooking? Yes/No.

13. Can you fit all your pots on the cooking ports? Yes/No. If not, what alterations could be made so that these pots can fit? .....
.....

14. Has your stove cracked or deteriorated in any way? Yes/No. How? ....
.....

15. How often do you have to maintain the stove so that it functions to your satisfaction? .....

16. How could the stove be made more durable? .....
.....

17. Do you find the dampers easy to use? Yes/No.

18. Have you lost any of the dampers? Yes/No.

19. Have you made any changes to the stove? Yes/No.
What changes have you made, and why? .....
.....
.....

20. Do you use hot water provided by the stove for purposes other than cooking? Yes/No. If so, what? .....
.....

21. Does the stove provide enough heat to keep you warm? Yes/No.

22. What changes would you like in your stove? .....

.....

.....

Questions relating to diffusion

23. Did you build the stove yourself? Yes/No. If 'yes', answer questions 24-26; if 'no', answer question 27.

24. How much did the materials cost? .....

25. How long did it take to get them? .....

26. Who helped you build it? Family (specify relationship) .....

.....

Other (specify) .....

Did you pay them? Yes/No. If so, how much did their labour cost you?

.....

How many man-hours (approx.) did it take to build? .....

27. If you did not build the stove, how did you obtain it? .....

.....

If you bought it, how much did it cost? .....

Who did you buy it from? .....

28. Did you receive instruction on:

a) How to build it: Yes/No.

b) How to maintain it? Yes/No.

c) How to operate it? Yes/No.

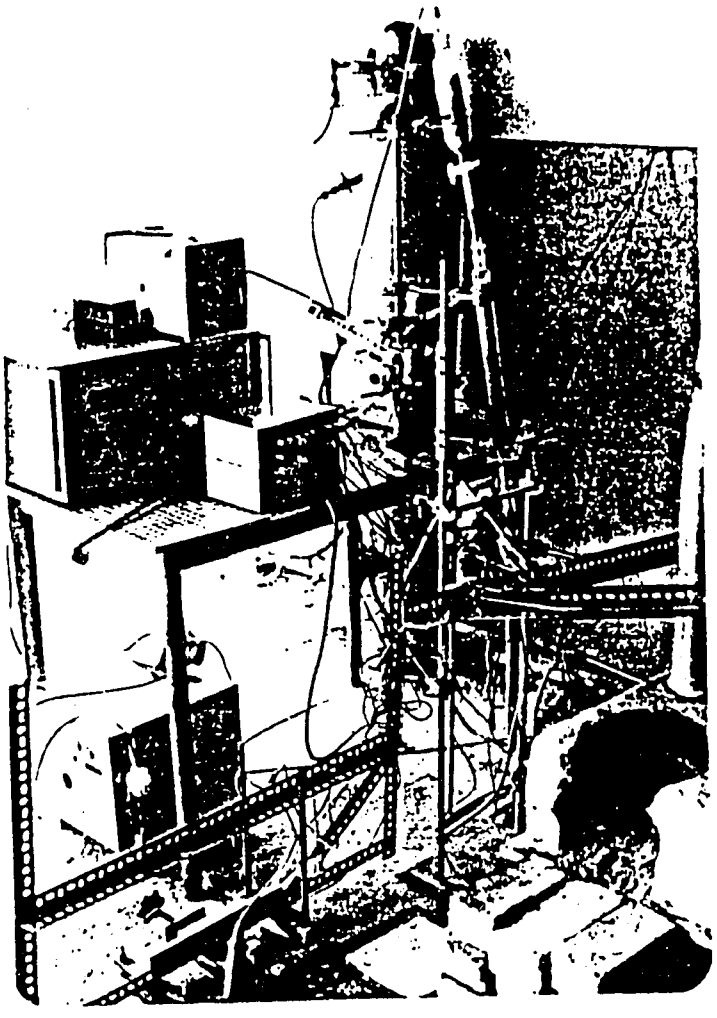
29. Has any extension agent or entrepreneur visited you to provide further training or assistance? Yes/No.

30. What further courses would you benefit from? .....

31. Have you helped anyone else to build a stove? Yes/No.

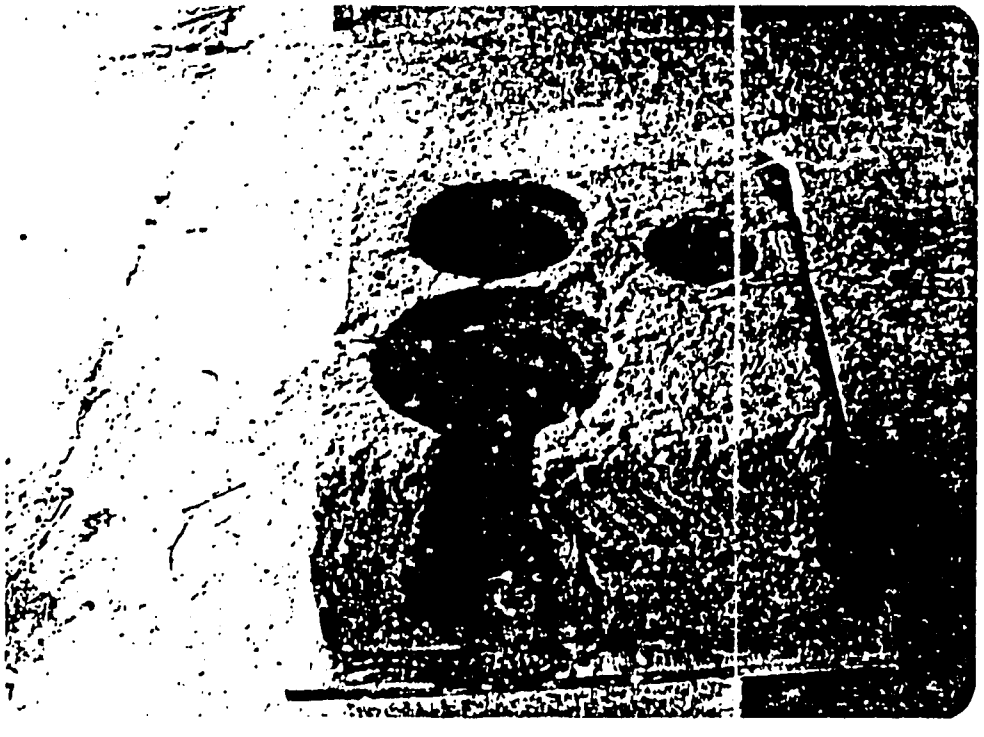
If so, give details .....

.....



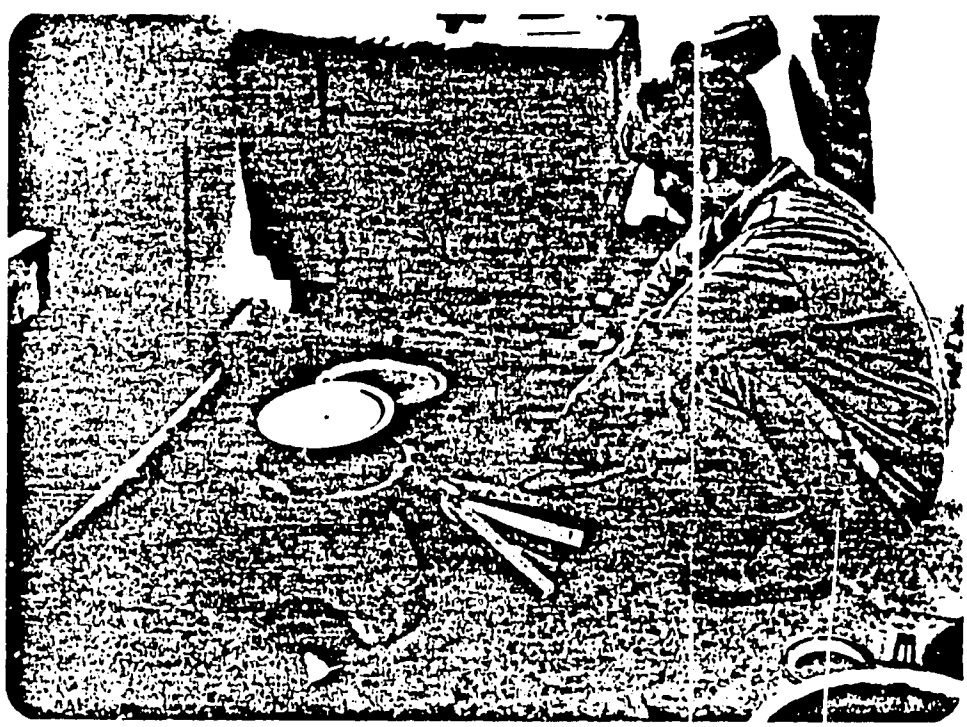
Test Rig - Sensors

Test Rig - Scale



Mud stove after testing

Models being tested



Test in progress