

# Renewable Energy Development in Africa

## Volume 2



Commonwealth Science Council

# **Renewable Energy Development in Africa**

## **Volume 2**

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## **INTRODUCTION**

### **Background**

In September 1979, a group of African researchers met in Arusha, Tanzania under the auspices of the Commonwealth Science Council. The main objectives of the meeting were to share their experiences and to explore the feasibility of establishing a regional programme of research and development activities on renewable energy technologies and their application in Africa. The meeting, which identified seven projects to form the basis of collaborative research projects in the region, led to the formal institution of the African Energy Programme (AEP) by the Commonwealth Science Council (CSC). In addition to the AEP, similar initiatives were launched by other national and international bodies to promote and harness the enormous renewable energy potential of Africa.

The AEP aims to promote work on the African continent in the field of renewable sources of energy and to co-ordinate and strengthen the African scientific and technical capabilities through cooperative activities. The Programme is concerned mainly with addressing the energy needs of the predominantly rural populations of Africa with the following eight projects forming the nodal points for collaborative research and development:

1. Biogas for rural development
2. Energy policy for planning
3. Resource assessment
4. Solar crop drying
5. Solar heating and cooling
6. Wind electricity generation
7. Wind water pumping
8. Wood/charcoal production and utilisation.

The major activities of the AEP fall into three broad categories:

1. National scientific research and technological development as part of a regional network.
2. Workshops whose main objectives are:
  - to provide training to developing country scientists in the techniques and methodologies for high quality scientific research;
  - to identify common areas for follow-up training through collaborative scientific research and technological development;
  - to provide fora for the interchange of ideas and comparison of scientific results and information derived from the application of common methodologies.
3. Training courses and fellowship attachments.

The common theme underlying all activities is to assist with the development of indigenous scientific and technological capability around common disciplines and methodologies.

The United Kingdom Overseas Development Administration (ODA) has provided substantial financial support to initiate research and development activities on three of the projects: Solar crop drying, Charcoal production and utilisation and Biogas systems. Activities in the other projects have been pursued through national programmes and a number of training workshops organised by the Commonwealth Science Council. The range of projects has been instrumental in demonstrating the practicability of a regional network approach to science and technology for development within the constraints of scarce human and institutional resources.

The International Conference on Research and Development of Renewable Energy Technologies in Africa was organised to offer the opportunity for the scientists working on the AEP to share their results and experiences with each other, as well as with colleagues working on similar problems elsewhere in Africa and other countries. The specific objectives of the Conference were:

- to report the results of research projects on renewable energy technologies in Africa covering both the activities of the African Energy Programme and those of other institutions/agencies;
- to provide an opportunity for international exchange of research ideas and information between African scientists and colleagues from elsewhere;
- to provide a forum for scientists and potential donors to explore modalities for future collaboration on energy research and development in Africa.

#### **Organisation and management**

The Conference took place at the Paul Octave Wiehe Auditorium of the University of Mauritius from 25-29 March 1985, and was attended by 100 scientists, researchers, policy makers and representatives of International Organisations from 30 countries.

The programme consisted of plenary technical sessions which discussed invited and submitted scientific papers under four generic schemes of **Resource Assessment; Energy Conversion Technologies; Energy Utilisation Technologies; Energy Policy and Planning and International Collaborative Programmes**. In all, about 70 papers were presented at the Conference. In addition, visits were organised to the Bagasse-fuelled power station at Champagne and the Renewable Energy Projects of the University of Mauritius.

The Conference was officially opened by His Excellency Sir S Ramgoolam, Governor-General of Mauritius. The Inaugural address was delivered by the Hon A K Gayan, Chairman of the Council of the University and Minister of External Affairs for Mauritius. Professor J Manrakhan, Vice-Chancellor of the University of Mauritius delivered the keynote address to the conference. Dr P Hutchinson, Deputy Secretary of the Commonwealth Science Council, welcomed the Conference delegates on behalf of the Secretary-General of the Commonwealth and the Chairman and Secretary of the Commonwealth Science Council.

## **Conclusions and recommendations**

### **1. Organisation of the AEP**

Since its inception, the African Energy Programme activities have covered a number of fields concerning energy resources. Some activities had been more successful than others. However it was clear that the Programme had fulfilled a need, and should be carried on and expanded.

Such expansion should, in the first instance, be in the inclusion of non-Commonwealth African countries. The attendance at the Conference of representatives from these countries already initiates such a step.

Representatives of the International Organisations outlined their various activities in the field of energy, emphasising thus the advantage of close co-operation between the various agencies within a single system or network. The UNEP representative indicated that his organisation was considering a round table meeting of agencies concerned with energy. The suggestion was noted that a full time Secretariat would be beneficial, though the difficulties of acquiring funds for this were noted.

### **2. Technical development**

#### **1. Exchange of information**

The need for exchange of information was strongly expressed. It was mentioned that there was, perhaps, too much information available. However, the difficulties of exchanging the information had often led to the duplication of effort. What was required was a system for organising and selecting the information as well as the means for delivery to and between the scientists and engineers.

Several organisations had made a start, for example, the Solar Energy Society for Africa had come into being, and frameworks also existed with the African Network for Scientific and Technological Institutions (ANSTI) and the African Energy Commission. The UN agencies were also interested in becoming involved in information systems for energy.

The conclusion was clear that the time was ripe for an African Energy Information System.

#### **2. Application of technology**

There was consensus that sufficient scientific and technological knowledge had been accumulated in many aspects of Energy for the balance of effort to be tipped towards the application of the knowledge to development.

It was important that several avenues for implementation be investigated. These range from governmentally-sponsored schemes to those which were purely commercial. In the latter case, the involvement of entrepreneurs, manufacturers and sales people from the start of any project is important.

It was considered that it was insufficient merely to present to the public devices for the utilisation of energy. It was important to create a demand, for example, for dried products, which in turn would provide a demand for the implements.

3. Training

The need for appropriate training was expressed. Some courses already exist in the developed countries. However, the development of such courses within the region would be useful.

Not only was there a need for graduate training, but training of support staff at technician level was also a requirement.

4. Priorities

1. It was recognised that countries would each have their own priorities as far as the various aspects of energy utilisation were concerned. In general, though, Biomass utilisation, particularly that through biogas generation, and the design of solar appliances was well advanced. Two areas specifically mentioned requiring further work were pyrolysis and collection of solar and wind energy data.
2. Co-operative action, both on an organisational level between agencies, and by information exchange was seen as an essential way to optimise the effort which was going into the development of energy.
3. Taking the results of research and development to energy application through the medium of commercialisation was seen as the next major step forward.
4. Training at all levels, and by several means, was, as always, seen as an essential output.

**C Y Wereko-Brobby**  
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## **A. SOLAR CROP DRYERS**

**INTERACTION BETWEEN TEMPERATURES, AIRFLOW AND  
CHIMNEY DESIGN IN INDIRECT FREE CONVECTIVE  
SOLAR DRYERS**

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**ABSTRACT**

This paper presents the results of experiments using two indirect free convective solar dryers under no-load and loaded conditions using rice, under typical conditions existing in Sierra Leone. One of the dryers has a single passage in the air heater and the other a double passage air heater. Five different chimney configurations were used. The performance of the two dryers was compared in relation to mean daily chamber and chimney temperatures and mean daily solar radiation intensities. A short chimney (about 50cm) painted black and covered with transparent material was the most effective configuration. A single air passage heater appears to be more appropriate for use with free convective solar dryers.

**INTRODUCTION**

The use of solar dryers in rural areas of Africa has been severely restricted because of the low air flow rates existing in natural convection dryers. Owing to the low income of farmers and the absence of electricity, dryers for rural applications generally do not have a mechanical means, such as a fan, to circulate warm air through the crops.

Efforts to design a solar crop dryer which circulates air effectively through only free convection have proved disappointing. However, this can be achieved by systematic investigation of the operation of dryers under real life or simulated conditions. Although dryer designs have been discussed extensively (Brace Research Institute 1975; Exell 1980), there is apparently no published work which has studied the interaction between dryer design, ambient conditions and airflow.

Bassey (1982 a) has described the effect of various chimney designs on the temperatures obtained in an indirect solar dryer using an air heater with two air inlet channels. The study showed that it may not under all ambient conditions be useful to have tall chimneys on free-convective dryers. Furthermore, results indicated that the chimneys in these dryers should be designed so as to minimise heat losses from them.

This paper presents results of a study aimed at describing the complex response of indirect free-convective dryers to their environment. The performance of two dryer designs was assessed using five chimney configurations under various ambient conditions existing in Sierra Leone, under no-load and loaded conditions using rice.

## **EXPERIMENTAL APPARATUS**

### **Solar dryer design**

The general front and side views of the dryers are shown in Figures 1 and 2. They are identical except in the design of the air heater. Dryer 1 has a single air passage (4 cm high and 70 cm wide) between the absorber plate and the glass cover as shown in Figure 3. Dryer II (Figure 4) has two air passages (both 70 cm wide) separated by the absorber plate. The heights of the top and bottom passages are 4 and 2 cm respectively. The glass covers are approximately 90 cm by 90 cm in surface area and are attached to the solar collectors using wood putty.

The air heaters are connected to the drying chambers by means of a rectangular channel equal in cross sectional area to those of the air passages. Both dryers are mounted such that the air heaters are inclined facing south at an angle of about 20 degrees to the horizontal.

### **Chimney configurations**

Five detachable chimneys of different configurations were used. All were made of 0.16 cm galvanised iron sheeting and each had an internal diameter of 15 cm. Their special features were:

- (a) 38 cm high, unpainted;
- (b) 38 cm high, painted black outside;
- (c) 38 cm high, painted black outside, surrounded by transparent plastic;
- (d) 180 cm high, painted black;
- (e) 180 cm high, painted black outside, surrounded by transparent plastic.

The transparent cover acts as a solar collector. There is an air gap of 2 cm between the blackened outer wall and the plastic surround. Care was taken during construction to ensure that the plastic did not touch the chimney walls during operation.

### **Instrumentation**

Temperatures were measured at several positions on the dryers, as shown in Figures 5 and 6, using copper constantan thermocouples connected to a ten-point thermo electric temperature indicator or a portable "Digimite" indicator, both accurate to 0.5°C.

Total solar radiation on a horizontal surface was measured using an Epply precision spectral pyranometer connected to an electronic integrator and printer. The output in units of Wh/m<sup>2</sup> was recorded at 10 minute intervals. Wind speeds were monitored during the experiments using a hand held cup anemometer.

## **METHODS**

### **Tests under no-load**

The dryers were operated using different chimney configurations for the 8 hour period 0800-1600 hours. The temperatures at the locations shown in Figures 5 and 6, total solar radiation on a horizontal surface, wind conditions and other

ambient conditions were measured at regular intervals. All experiments were repeated over several days, over a period of three years.

### **Tests under load using rice**

Two sets of experiments were carried out with the dryers under load. In the first tests performance was compared when loaded with a rice bed 2.5, 5.0, 7.5 and 10 cm high. The rice was supported on a single tray in each dryer, situated above the inlet into the drying chamber. During these tests, a 38 cm, unpainted, chimney was used.

In further tests with similar bed depths as above, chimneys 38 and 180 cm high and painted black and covered with a transparent plastic cover were used in dryers I and II respectively.

The drying period for each bed of rice lasted several days to reduce the moisture content to the required value.

## **RESULTS AND DISCUSSION**

### **Temperatures in dryers under no-load**

Plate temperatures were the highest. These ranged from 80 to 100°C, depending on the solar radiation in dryer I. In dryer II, the temperatures at the top of the plate were generally lower than those of dryer I. There was a 40°C temperature difference between the two sides of the absorber plate for dryer II.

Temperatures in the drying chambers were less than 50% of the plate temperatures as a result of the low flow-rates through the air heaters.

### **Influence of solar radiation under no-load**

During all experiments, total solar radiation was measured and recorded every 10 minutes from which solar radiation intensities were estimated. Mean values of intensity of solar radiation for a whole day were estimated by dividing the total energy for that day by the period of the test.

Figures 7 and 8 show the effect of mean intensity of radiation, on chamber temperature for various chimney configurations.

Chamber temperatures are generally higher for higher availability of solar radiation. However the chamber temperatures for lower mean radiation intensities are at times very close to or greater than temperatures for higher intensities (Figure 8c). This behaviour can be related to the variation of solar radiation during the experiments. Under cloudy conditions the chamber temperatures could be significantly lower.

In all cases temperature in the chamber was between 30 and 50°C. This indicates the potential usefulness of indirect free-convective solar dryers.

The variations of daily mean chamber temperature with mean solar radiation intensity for all the chimney configurations studied are shown in Figure 9. The scatter in the data results from the intermittency of the available solar energy due to cloud cover. It is possible to have the same mean solar intensity on two days although the mean temperatures for those days may be different.

### **Effect of type of chimney used under no-load**

Chimney configuration affects the mean chamber temperature under no-load. In dryer I chamber temperature increased with a black chimney and increased further with a plastic cover. Increasing the height of the chimney decreases the temperature in the chamber. In dryer II chamber temperature decreased with a 38 cm chimney painted black and further decreased with the transparent cover in place. Increasing the height of the chimney tends to increase the chamber temperatures.

These results can be explained by the flows through the dryers as a result of the interaction of the chimney design, the air heater and the surroundings. In dryer I the chamber temperature is obtained as a result of ambient air being heated as it passes through the single channel heater. If the chimney is painted black, it is now heated by solar radiation causing a slightly higher flow rate through the air heater. As a result the chamber temperature is increased. If the blackened chimney is covered with a transparent cover, the heat losses from the chimney are minimised, resulting in higher temperatures inside it, this in turn causes higher buoyancy forces which increases the air flow. Increasing the height of the chimney tends to increase heat losses from it which in turn decreases the flow rates: the temperatures in the drying chambers are thus lowered.

In dryer II the effects of chimney configuration is reversed. This is a result of the increased flow rate causing a greater influx of cooler air introduced through the bottom channel.

Reasonable operating temperatures can be obtained in indirect free convective dryers. However, air flow rates can be very inadequate as a result of chimney design. Many solar dryers have tall and at times black chimneys which may in fact decrease airflow rates depending on the prevalent ambient conditions such as the incidence and duration of clouds, wind and fluctuations of ambient temperatures. For conditions existing in Sierra Leone, detailed examination of data has consistently supported this argument.

This problem of the adverse effect of chimney design and the above explanations are further reinforced by considering the relative magnitudes of chimney and chamber temperatures. Although temperatures in the chimney are usually higher than those in the drying chamber, under low solar radiation conditions this is not so (Figure 10). In dryer I with 38 cm unpainted chimney temperatures are generally lower and in dryer II with a 180 cm black chimney significantly lower during the whole day. Days for which the above type of results are typical had relatively low levels of solar radiation, frequent and prolonged cloud cover, and either low ambient temperatures (depending on the season) or windy conditions.

### **Temperatures in chimney and chamber under load**

Rice at initial moisture contents ranging from 25% to 45% (dry basis), depending on the degree of soaking, was used during the on-load tests. Based on earlier discussions, the relative magnitudes of temperatures in the chimney and drying chamber give an indication of airflow through the dryer. Figure 11 shows chimney and chamber temperatures for two heights of the rice bed for dryer I. In both cases the solar radiation conditions were similar. With a rice bed 2.5 cm high, the chamber temperatures (below the rice bed) are higher than the chimney temperatures throughout most of the day. Early in the day, the chimney temperatures are higher. Results for the 7.5 cm rice bed are similar but the temperatures are relatively lower.

These data are consistent with the preceding discussions. Increase in the height of the rice bed should reduce the flow and for the single channel air heater this implies a drop in chamber temperature.

For prototype II (Figure 12) a reduction of airflow due to the deeper rice bed produces a higher temperature in the chamber (underneath the bed) than in the chimney. This is expected from results under no-load conditions and further emphasises the potential flow problems in free convective dryers. It is possible that these lower chimney temperatures, caused by the air being cooled by water from the crop, can substantially lower the flow rate. Adverse ambient conditions earlier discussed and poor chimney design can make such dryers very inefficient.

Under load, Figure 13 shows that for 5 and 10 cm deep rice beds, dryer I gives lower cabinet temperatures than dryer II although the former has higher plate temperatures.

### **Overall significance of results**

The preceding discussion indicates that the flows through indirect free convective dryers are governed by many complex parameters. Some of these are: the chimney design, the air heater design, the ambient temperature, cloud cover, available solar radiation and wind conditions.

Results suggest that in the design of this type of dryer the single channel air heater may be adequate considering its relative performance to the double channel heater. The use of tall black or unpainted chimneys is unsuitable under atmospheric conditions where cloud cover, low solar radiation intensities and wind may exist. Under these conditions a 50 cm chimney painted black and covered with transparent plastic is recommended. However under clear sunny conditions, tall chimneys may prove to be more advantageous. Thus the overall design of free convective dryers are location specific.

Another important implication of the results is that during drying, the temperature in the dryer above the crops is substantially lower than that underneath. Thus in the design of these dryers there should be a revision of the usual assumption of constant densities in the dryer to take into account density changes throughout its height. (This has been treated elsewhere, Bassey (1982 b.) In order to do this, results such as those obtained in this study can be very useful.

In addition, experience gained during the course of the study suggests that an experimental study aimed at assessing the effects of all the relevant parameters is very tedious. Specific aspects need to be scrutinised in future experimental activities. In order to understand the response of the dryers to various conditions a next step should be the mathematical modelling of free convective dryers using realistic inputs such as those reported in this paper. Such a strategy could rapidly identify areas for further experimentation leading to better dryer designs.

### **CONCLUSIONS**

The following main conclusions can be drawn from this paper:

- (a) The interaction of various parameters makes the study of indirect free convective dryers very complex. It is however possible to quantify their

overall performance by relating mean daily temperatures in the drying chamber to mean daily intensities of radiation.

- (b) In general, the type of chimney used affects the flow of air through the dryer. For cloudy, low solar radiation conditions existing in many tropical areas, it is advisable to use short chimneys (about 50 cm high) painted black and with a transparent cover around it. Taller chimneys may suffer substantial heat loss.
- (c) Air heaters with a single air passage are considered more appropriate for use on free convective solar dryers due to their simplicity in design and generally higher temperatures.
- (d) Results presented can be used as a basis for carrying out analytical modelling studies with a view to improving dryer performance.

### **ACKNOWLEDGEMENT**

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Exell R H B (1980) Basic design theory for a simple solar rice dryer. Renewable Energy Review Journal. 1 (2), 1.

Brace Research Institute (1975) A survey of solar agricultural dryers. Brace Research Institute Technical Report T99.

FIGURE 1: General front view of dryers

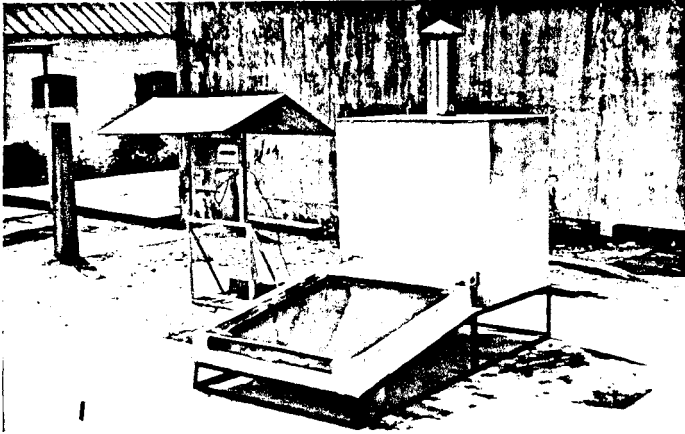
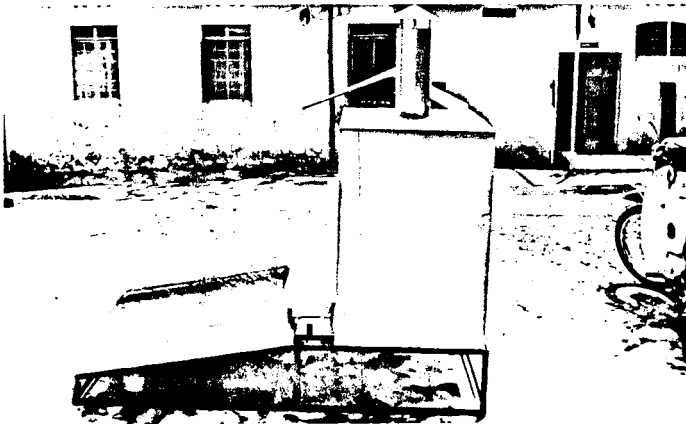
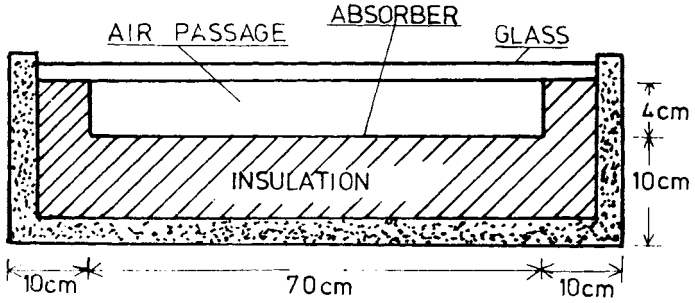


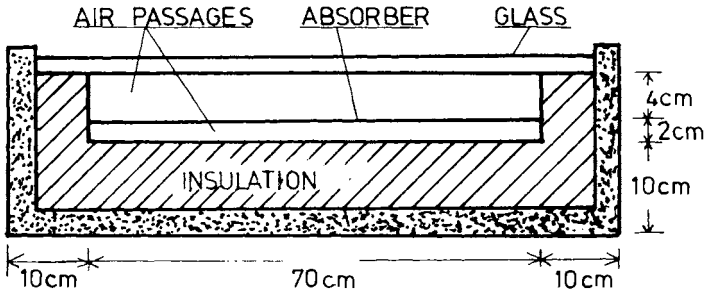
FIGURE 2: General side view of dryers



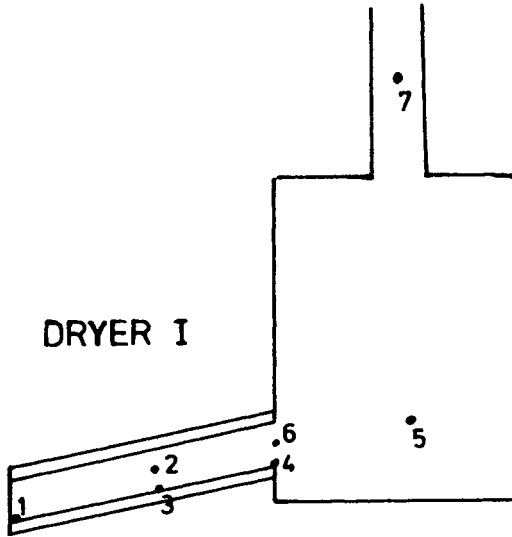
**FIGURE 3: Cross-section of air heater for dryer I showing the single air passage**



**FIGURE 4: Cross-section of air heater for dryer II showing the double air passage**



**FIGURE 5: Diagram showing location of thermocouples in dryer I.**



**FIGURE 6: Diagram showing location of thermocouples in dryer II.**

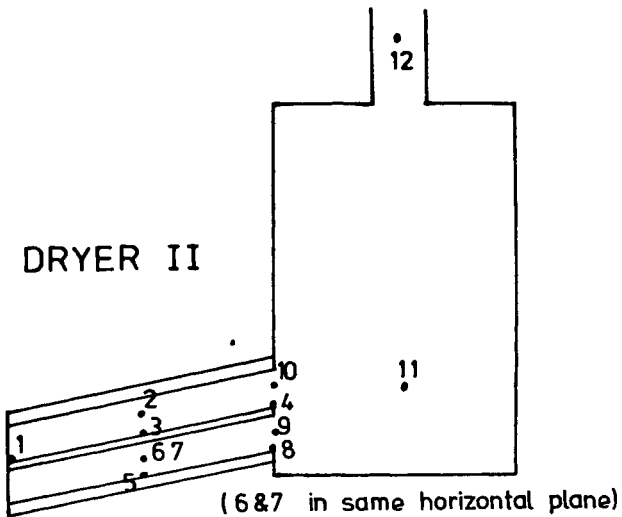


FIGURE 7: Effect of mean radiation intensity on chamber temperature for various chimney configurations, for dryer I.

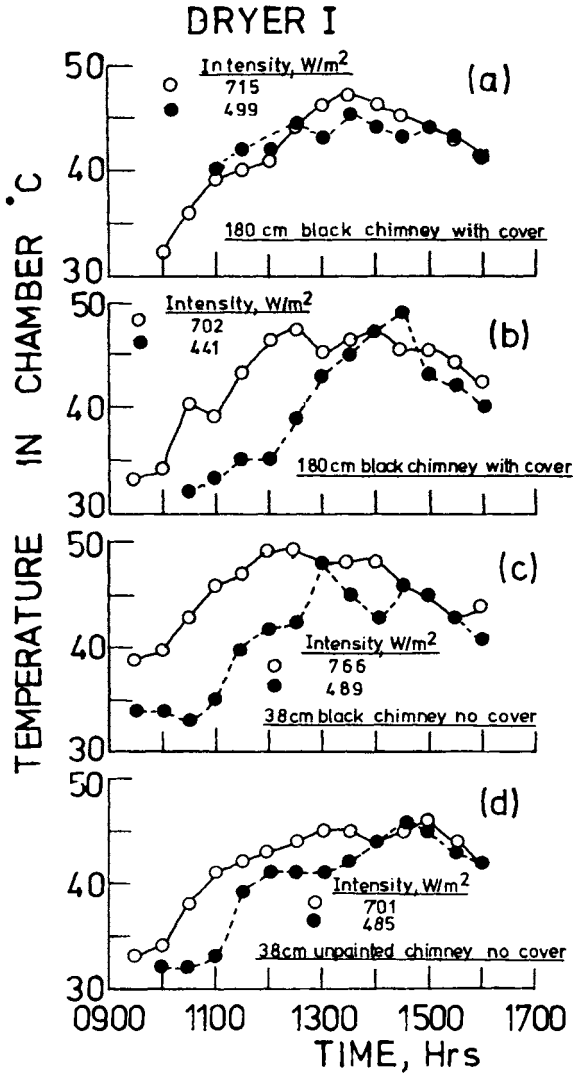


FIGURE 8: Effect of mean radiation intensity on chamber temperature for various chimney configurations, for dryer II.

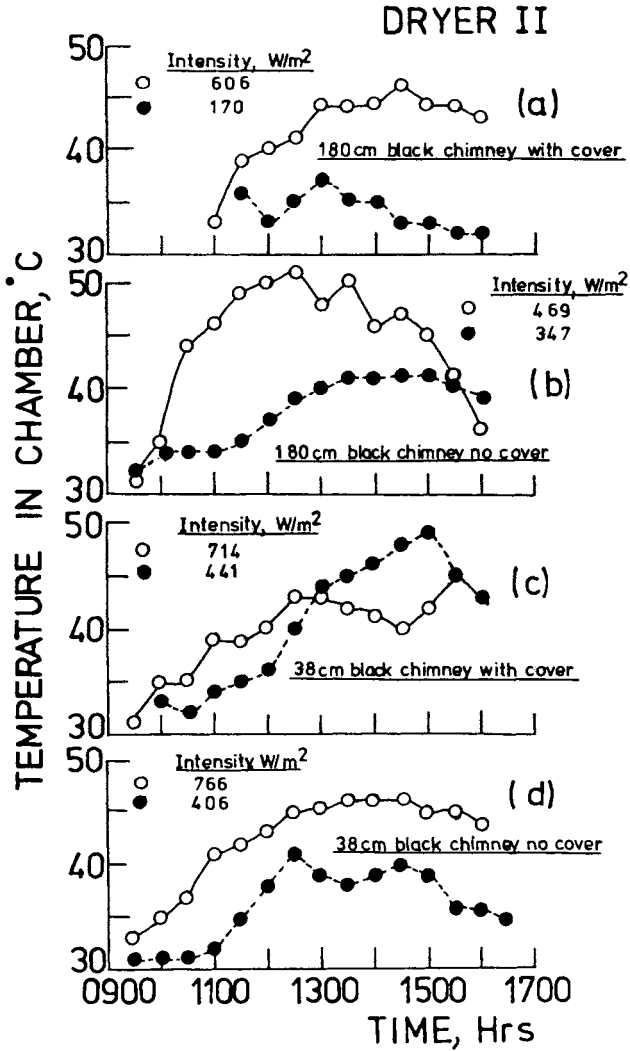


FIGURE 9: Effect of air heater design and mean solar radiation intensity on mean chamber temperatures under no load.

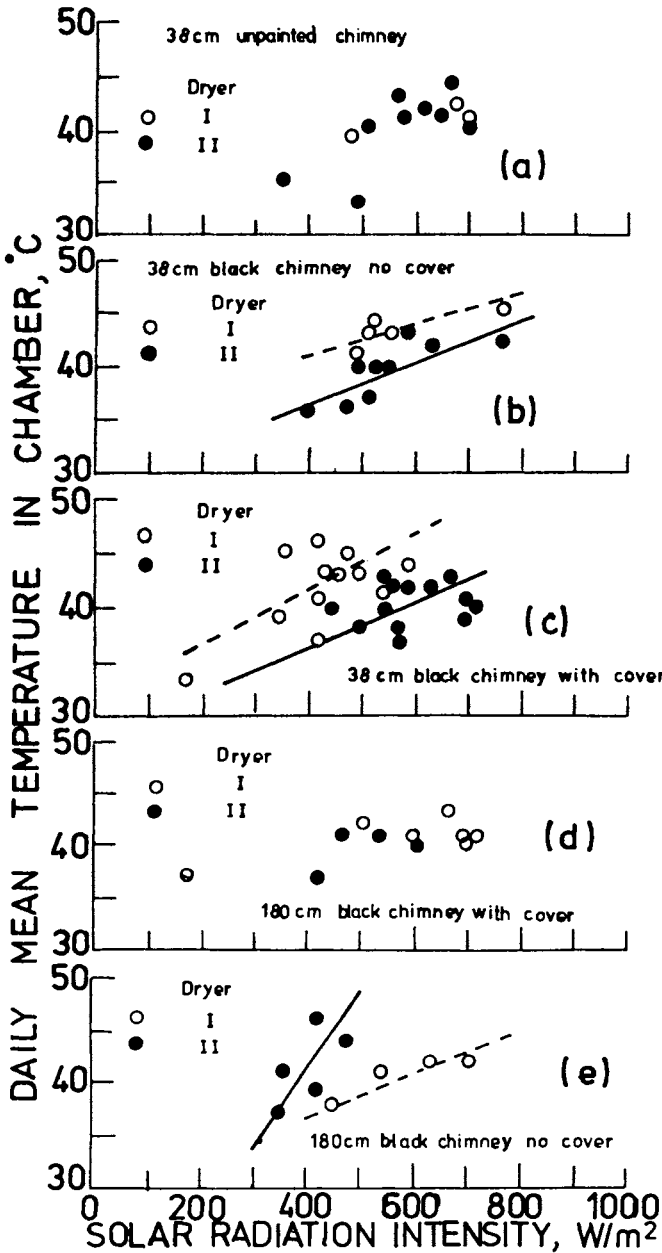


FIGURE 10: Comparison of temperatures in chimney and in drying chamber for dryers I and II, under no load conditions.

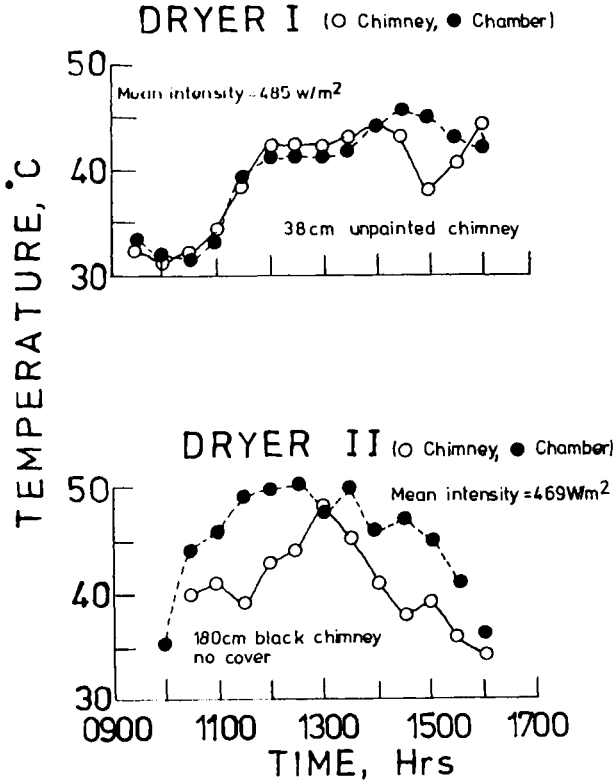


FIGURE 11: Temperatures in chimney and drying chamber during tests using rice, for dryer I.

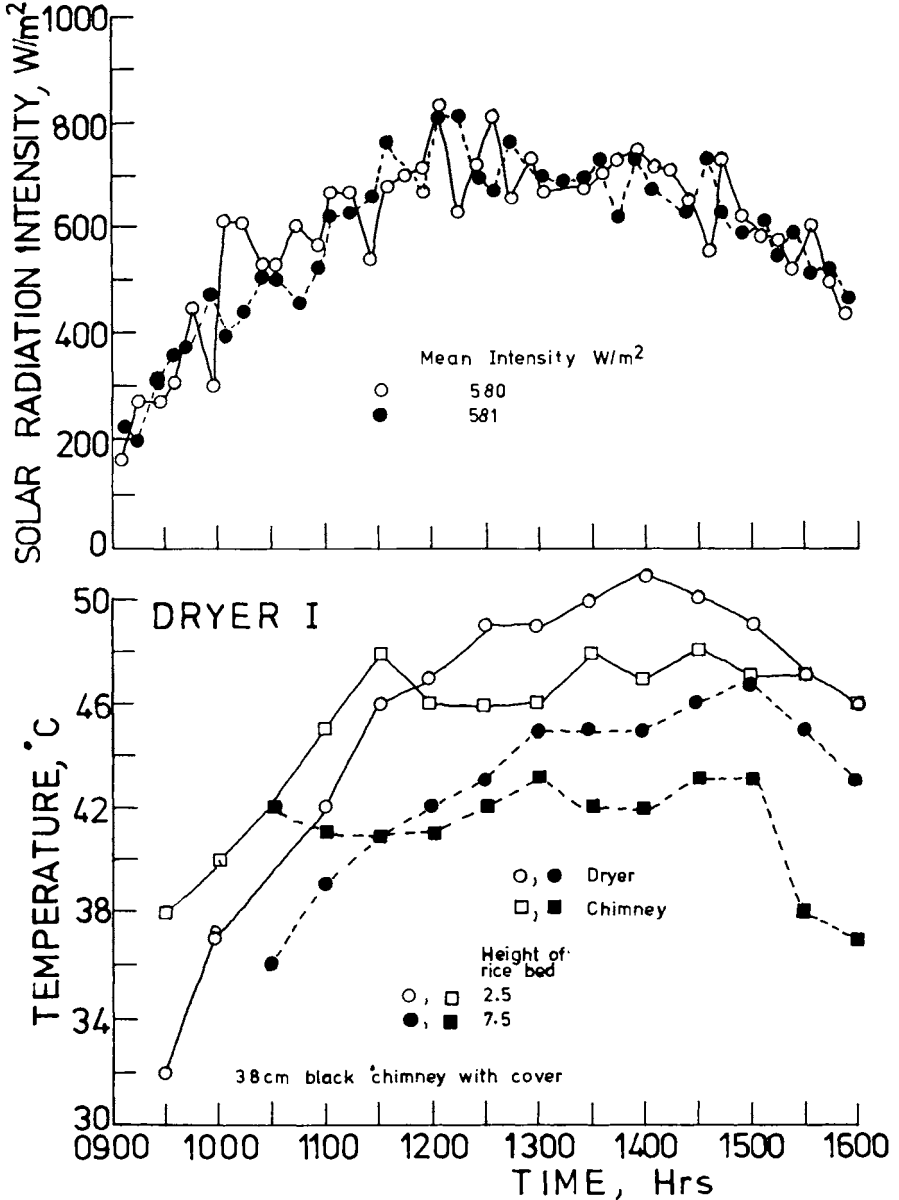


FIGURE 12: Temperatures in chimney and drying chamber during tests using rice for dryer II.

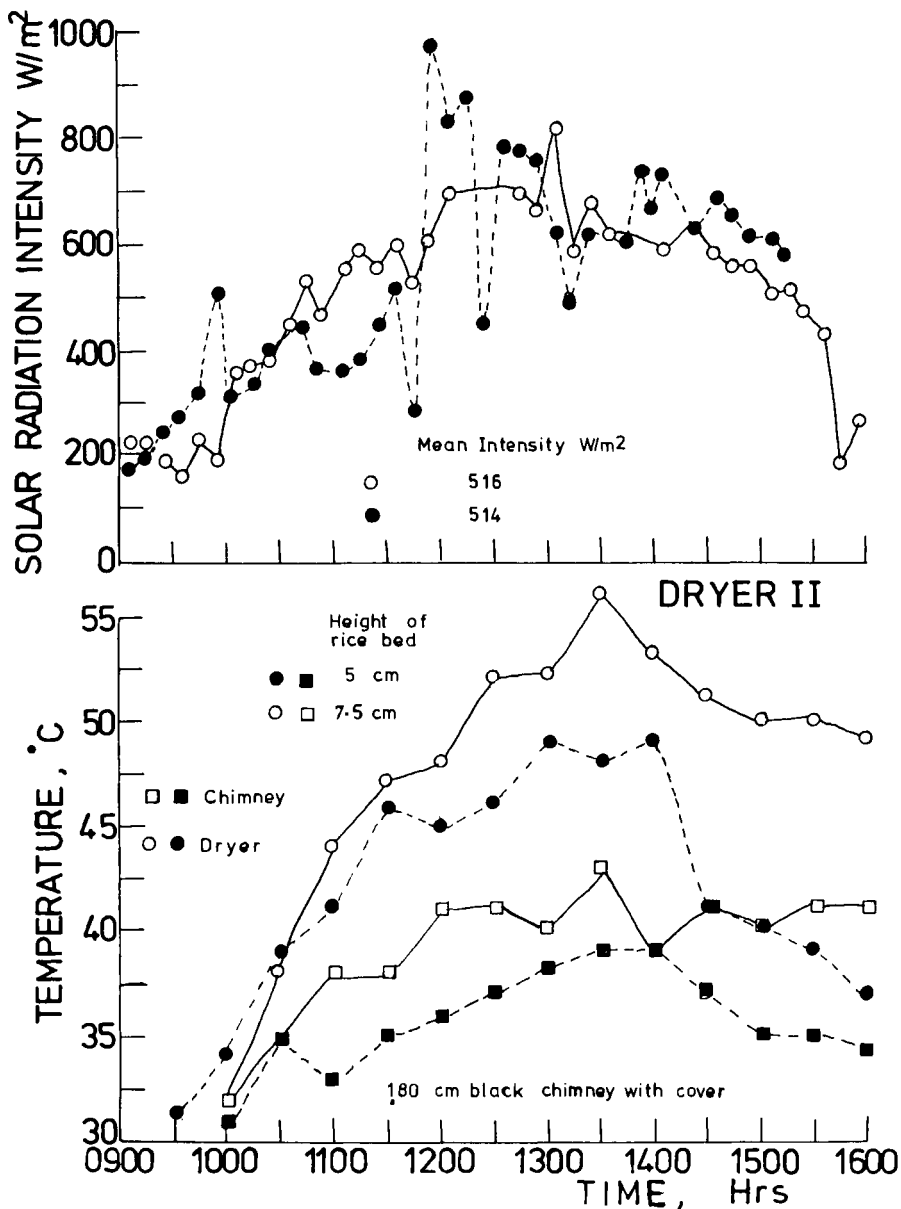
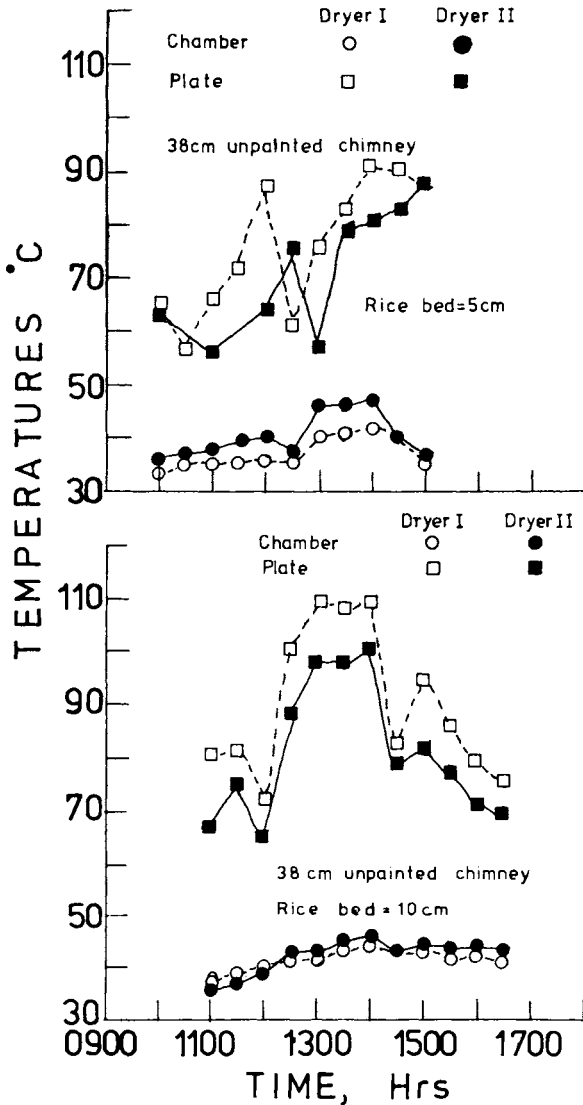


FIGURE 13: Effect of air heater design on chamber and absorber plate temperatures, under loaded conditions.



## **OPTIMISATION OF SOLAR AIR HEATING COLLECTORS USED FOR CROP DRYING**

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### **ABSTRACT**

This paper describes theoretical analyses applied to the optimum design of two types of solar crop dryers. One uses a flat plate solar collector and the other a multilayered one. The design specification was to reduce moisture content of 90kg of shelled maize from 20% to 13% moisture content, wet basis, in one day. The dryer with a flat plate collector achieved only a third of the target drying rate. The design using a multilayered collector achieved higher temperatures but grain drying duration was not substantially reduced. Using the theoretical analysis and experience with the two experimental dryers, a suitable prototype solar crop dryer was designed and constructed. For simplicity, the eventual design adopted had a flat plate collector.

### **INTRODUCTION**

Traditionally, many cereal crops, vegetables and fruits are dried by thinly spreading them on prepared ground in open sunlight. Generally, there are large losses of product due to dispersal by wind and destruction by rodents, birds and domestic animals. Moreover, the traditional drying method is not easy to control and overheating can occur, making insect penetration easier and hence high storage losses. Rewetting and overdrying in variable weather conditions can also cause some losses and reduction of the quality of the product.

In the case of maize, it has been reported (Moody 1980) that losses increase with time when maize is left in the field after maturing. Losses of up to 22% after two months, increasing to 50% after three months have been reported in the humid tropics. In order to reduce such losses, maize must be harvested as soon as it matures and then dried.

In recent years, attempts have been made to reduce post-harvest losses and also improve the quality of the product by using small scale solar drying devices. For example, a solar air heater can be designed to supply warm air to the product placed in a safely locked cabinet.

This paper describes theoretical analyses of the optimal specification for flat plate and multilayer solar collectors. Two prototype dryers were designed with the expectation of drying 90kg of shelled maize from 20% to 13% moisture content, wet basis, within one day.

The paper outlines the further optimisation of these crop dryers and the final prototype constructed for use by farmers in Kimalewa, Bungoma, and Homa Bay. The choice of prototype design was governed both by performance characteristics and the need to produce a design that is simple for farmers to construct.

### **ANALYSIS OF THE COLLECTORS**

A very large, and hence expensive, collector would be capable of drying a small quantity of grain in a very short time. The aim of optimisation is to reduce this

ratio of collector size to quantity of grain by increasing the efficiency and hence decreasing the necessary size of the collector.

### Flat plate collector

In order to optimise the collector design, it is necessary to understand the processes of heat and mass transfer inside the collector. The analysis of these processes is complicated due to the constantly changing environmental conditions. However, if some simplifying assumptions are made, as discussed by Othieno (1983), heat balance equations can be formulated and solved analytically. These equations for a simple flat plate collector (Figure 1) are given below:

For the transparent cover:

$$h_{go}(T_g - T_o) + h_{ga}(T_g - T_a) + \sigma \epsilon_g (T_g^4 - T_s^4) + \sigma \epsilon_g (T_g^4 - T_p^4) = \tilde{d}_g G \quad (1)$$

Sum of power lost by convection to ambient and air stream	+	sum of power lost by radiation to sky and collector plate	=	solar power gained by the transparent cover
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For air stream through the collector:

$$h_{ga}(T_a - T_g) + h_{pa}(T_a - T_p) = \rho d_a c_p \frac{\Delta T_a}{\Delta X} \quad (2)$$

For the bottom absorber plate:

$$\sigma \epsilon_e (T_p^4 - T_g^4) + h_{pa}(T_p - T_a) + k_e (T_p - T_o) = g (\theta) \alpha_p G \quad (3)$$

The temperatures of the transparent cover ( $T_g$ ), the air stream ( $T_a$ ) and the black absorber plate ( $T_p$ ) vary in the direction of air flow. Therefore the above equations can only be valid for a small section of the collector of length  $\Delta X$  where the temperatures can be assumed to be uniform.

The solutions of these equations for an optimised flat plate collector are shown in Figure 2. Theoretically the highest air temperatures would be achieved when the collector depth,  $d$ , is close to zero. However, in practice if the collector depth is too small, the air significantly cools down when it reaches the crop bin because of the available large volume for expansion. Furthermore, as the collector depth is reduced, the air flow pattern changes thereby causing a drop of air temperature. This means that there is a minimum collector depth below which overall heat loss increases so fast that efficiency drops. It has been suggested (Macedo and Altamani 1978; Grainger *et al.* 1981; Grainger 1982) that this depth should be about 5 cm.

In this work, it was confirmed that a depth of 5 cm does not allow adequate air flowrate through the grain. Thus the collector depth should be more than 5 cm if a reasonable amount of grain is to be dried within the desired period.

Collector efficiency is low due to the high heat losses caused by high cover and absorber plate temperatures. It was therefore necessary to:

- (i) reduce the heat losses
- (ii) improve heat transfer process to the air stream
- (iii) increase the volume flowrate of air

These requirements led to the development of a multilayer solar collector.

### **Multilayer collector**

A multilayer collector has two or more air ducts. The air streams can be completely isolated or joined by perforations in the partitioning absorber plates. Many types of multilayer collectors have been studied (Othieno 1983). This paper reports studies, on one design with perforations in the parallel partitioning absorber plates as shown in Figure 3. Due to the additional absorber plates, the multilayer collector must be deeper than the simple flat plate collector. The perforated layer increases the heat transfer area in contact with the air stream and hence improves the heat transfer process. Consequently, the temperatures of the absorbing surface including that of the transparent cover are low compared to those of a simple flat plate collector. This significantly reduced heat losses from the collector as shown in Figure 4. This is a graphical representation of the solutions to the mathematical model developed by Othieno (1983) for an optimised multilayer collector.

Optimising a multilayer collector is more complex. The number of perforated absorber plates, and hence the overall depth of the collector, depends on the energy transmittance of the perforations. This transmittance is referred to here as the void factor,  $F_v$ , to distinguish it from that of the transparent cover. The void factor of the perforations was measured using two similarly calibrated pyranometers. One measured the direct unobstrated solar radiation while the other measured the radiation under the perforated absorber. At normal incidence, this measurement was checked by calculating the ratio of the area of the holes to the total area of the absorber plate.

The optimum gap,  $\delta$ , between adjacent perforated absorbers and the void factor, depend on the effective diameter of each perforation while the optimum number of perforated absorbers depends on the void factor. After several experiments, it was established that the optimum number of perforated absorbers could be estimated using the expression:

$$F_v^n = 1 - F_v \quad (4)$$

The best distance between the layers,  $\delta$ , is  $3D$  (5)

Where  $D$  is the effective diameter of a single perforation. Having determined  $n$  and  $\delta$ , the collector depth,  $d$ , can be found from the expression:

$$d = \delta / (n + 1) \quad (6)$$

The width of the collector is determined by the total amount of energy required to dry the grain within the desired drying duration. The collector length, on the

other hand, is determined by the velocity of the air passing through it and the maximum air temperature required for the drying process. This length can be estimated experimentally or obtained from the solutions of the mathematical model.

### GENERAL DESIGN CONSIDERATIONS

In order to design a useful dryer, all the relevant environmental conditions and the drying requirements of the wet product must be known. In this work an optimised dryer was specifically designed to dry maize, but the method can be used to design dryers for any other products. The information needed includes:

- i. environmental data (insolation, wind speed, ambient air temperature, humidity).
- ii. the initial and final moisture contents and the quantity of grain to be dried.
- iii. the required drying time (duration) and any other limitations, for example, the safe maximum drying air temperature for the particular product.

The drying rate of any product is generally limited by the diffusion process of water from inside the material to the surface. At the surface, the drying process is defined by the properties of moist air. The relationships of these properties can be obtained from psychrometric charts for the particular location.

If the drying process was not limited by diffusion processes, the total energy required for drying a given quantity of grain could be estimated by using the basic energy balance equation:

$$m_{wa} \lambda_v = m_a c_a (T_{ai} - T_{ae}) \quad (7)$$

The mass of water,  $m_{wa}$ , can be estimated from the initial and final moisture contents,  $M_i$  and  $M_f$  respectively:

$$m_{wa} = m_w \frac{M_i - M_f}{100 - M_f} \quad (8)$$

The drying duration in days and the width of the collector are related by the expression:

$$t_d = m_w \frac{M_i - M_f}{100 - M_f} \lambda_v (WL \bar{\eta}_c \bar{\eta}_d E) \quad (9)$$

The numerator is the energy required to evaporate a mass of water,  $m_{wa}$  so as to reduce the moisture content of the grain from the initial moisture content,  $M_i$ , to the desired final moisture content,  $M_f$ , wet basis. The denominator represents the energy required per day to evaporate the water. The daily average efficiency,  $\bar{\eta}_d$ , should take into account the required energy to remove water from inside the grain to the surface.

If it were possible to balance this equation, the task of designing a dryer would be very simple and straight forward. But  $\eta_d$  and  $\tau_c$  are not known before the dryer is designed. However,  $\eta_d$  can be calculated from the estimated values of the temperatures of air entering and leaving the grain stack if grain depth, moisture content and drying time are known. Brooker et al (1974) suggested a drying equation which relates all these parameters:

$$\theta = \frac{2^Y}{2^Y + 2^d - 1} \quad (10)$$

Where  $\theta$  is the dimensionless air temperature,  $y$  is the time unit and  $d$  is the grain depth factor. For moisture ration, MR, the relationship is:

$$MR = \frac{2^d}{2^d + 2^Y - 1} \quad (11)$$

The grain depth factor and the actual grain depth,  $d_g$ , are related by the expression:

$$d = \frac{d_g (M_{dl} - M_{d,eg}) d \lambda_{vg}}{36000 m_a c_a t_n (T_{ai} - T_{a,eg})} \quad (12)$$

Where  $t_n$  is the period of half response for the crop at different initial moisture contents and for air temperatures. The equilibrium moisture content,  $M_{d,eg}$  and equilibrium temperature,  $T_{a,eg}$  at various relative humidities can be obtained from data given by Brooker et al (1974) for various cereals.

Since the temperature of air reaching the grain from the collector is known from the collector optimisation process, it is possible to select a suitable temperature for the air leaving the grain so that a suitable grain depth can be calculated from the drying Equation (12). Hence daily average drying efficiency,  $\eta_d$ , can also be calculated. Obviously, knowing the grain depth and the quantity of grain to be dried will make it possible to determine the crop bin area. For convenience, the collector width should be equal to the side of the bin to which the collector is connected.

For a natural convection dryer, it is necessary to know the buoyancy-induced flow and the pressure head created above the atmospheric pressure. The buoyancy-induced pressure which initiates the motion of air through the dryer is:

$$P_{ha1} = (\rho_o - \rho_{ai}) g H_1 \quad (13)$$

As air flows through the dryer, its pressure decreases due to wall friction and bends in the system. For an indirect crop dryer, the largest pressure drop occurs inside the grain stack. The magnitude of this pressure drop can be estimated from the expression:

$$P_{g1} = K (u_g)^2 d_g \quad (14)$$

Where  $K (u_g)$  is the pressure drop per unit depth of grain and is air velocity dependent such that any available pressure head above the surrounding atmospheric pressure will cause air-flow through the grain.

### Chimney height

Airflow through the dryer can be enhanced by the presence of a chimney, carefully designed for the purpose. Chimney design must consider the balance between forces which produce the flow against those which retard the flow. A chimney would be useful if it creates the Bernoulli effect to suck air into the dryer or if the air inside the chimney is warmer than the air outside so that there is an upward pressure drop in the chimney. In the latter situation, the rate at which air in the chimney cools down to ambient temperature determines the maximum height of the chimney. For example, if the air cools down to ambient air temperature within 1m height, then the chimney height should not be more than 1m. For a rectangular chimney, this maximum chimney height can be determined from the expression:

$$Q = U_c S_c H_c \frac{[(T_{ai} - T_{ae}) - T_o]}{2} \quad (15)$$

However, in natural circulation dryers, the air leaving the grain stack is generally moist and almost as cold as ambient air, and so the presence of a chimney may not have any effect ( $T_{ai} \approx T_{ae}$ ). In this case there is no need to have a chimney. This has been experimentally confirmed and therefore the dryers have been built without a chimney (see Figure 1).

### Design checks (steps)

The design of the whole dryer is complex. The procedure recommended here enables the designer to check the scale and likely operation when a specific crop is to be dried. It has been used when designing a number of crop dryers. The following are the steps to be taken:

1. Determine solar radiation at the location, maximum safe temperature for the crop, initial and final moisture content of the crop, and the desired drying duration of a known quantity of crop.
2. Estimate air mass flowrate through the crop stack and the width of the solar air heater and then calculate the required crop depth using Equations 10, 11 and 12.
3. Since the quantity of the crop is known and the crop depth has been determined, the cross-sectional area of the crop bin can now be determined.
4. Determine the average drying efficiency using Equation 10.
5. Obtain collector depth from the model analysis as outlined above, calculate air velocity through the collector and determine the collector length required to heat air to the maximum safe temperature for the crop.

6. Calculate the efficiency and width of the collector. Use Equation 9 to calculate the width. If the calculated width is not numerically close to the estimated width, take the calculated width and repeat the procedure from step 5. If the calculated width is within 80% of the estimated width, take the estimated width and calculate air velocity through the grain.
7. Compare the buoyancy-induced pressure and the pressure drop across the crop stack. If pressure drop across the crop is higher than the buoyancy-induced pressure, take a new smaller value of air velocity through the crop, obtain a new air mass flowrate through the crop and repeat the procedure from step 2. If pressure drop through the grain is much lower than buoyancy-induced pressure, take a new larger value of air velocity through the grain, obtain a new air mass flowrate and repeat the procedure from step 2. If buoyancy-induced pressure is slightly higher than pressure drop through the crop then the obtained dimensions of the dryers are well matched and the dryers can now be constructed.

Two dryers were constructed on the basis of theoretical analyses outlined above. In each case the specification was to dry 90kg of shelled maize from 20% to 13% of wet weight in one day. In practice, the dryer with a flat plate collectors only achieved a third the expected drying rate. The second dryer with a multilayered solar collector achieved higher temperatures but the grain drying duration was not significantly reduced.

The results of theoretical analyses and experiences gained with the two experimental dryers were used to further optimise the designs and to design a suitable prototype solar crop dryer. Prototypes were constructed and installed for use by farmers in Kimalewa, Bungona and Homa Bay.

### **CONSTRUCTION OF THE DRYERS**

The solar collector (air heater), crop bin and two trays were all separate units which could be easily removed for repair or replacement. The solar collectors were made of aluminium sheets painted with several coats of matt-black paint. In one case the collector plate was insulated at the back with a sheet of plywood. In general the back and sides of the collector plate should be insulated with 5 to 10 cm thick good insulating material (eg diatomite). The collectors were then covered with two sheets of transparent ultra-violet resistant polythene, leaving an air gap of about 5 cm between the cover and the collector plate. This size of air gap had been previously found to be the optimum for this type of air heater. For this air gap, the heater should be about 1m long so as to heat air to about 60°C when the insolation is about 1000W m<sup>-2</sup>. According to the Kenya Bureau of Standards, grain dried for human consumption should not be heated above 60°C during drying. However, since the grain temperature is generally lower than the drying air temperature, it is safe to use air temperatures up to about 70°C. Thus the collector length would generally be longer than 1 m but less than 3m.

The air heaters were each coupled to a crop bin which could take up to 90 kg of shelled wet maize. Thus, the crop bin had to have a volume of about 0.15 m<sup>3</sup> with a thin layer (less than 15 cm) of grain to allow unidirectional natural flow of warm air through the grain. Having determined the width of the solar collector that would provide enough energy for the required drying duration, it was simple to make the crop bin width the same as that of the collector. Grain depth of about 10 cm was found to produce a pressure drop of about the same value as the pressure difference created by the hot air in the heater.

Like the air heater, the crop bin should generally be properly insulated to minimise excessive loss of heat from the dryer. The dryers constructed in this work were however not insulated since the construction of insulation chambers would make the dryers too complicated for an unskilled person to construct.

Earlier, during the experimental stage, observations showed that the temperature of air inside the grain stack and the actual temperature of the grain were higher at the bottom of the stack than at the top. Thus the bottom layer of the grain dries much faster than the top layer. For this reason two trays were constructed to facilitate the removal of the bottom layer as soon as maize had dried down to the required moisture content. The top tray would then be moved to the bottom position with fresh wet maize placed at the top. This arrangement has made it possible to dry more maize per day than was originally considered in the design.

The air heater, facing South at Kimalewa and Bungoma and North at Homa Bay was inclined at an angle of about  $20^{\circ}$  to the horizontal. These collector orientations had been determined as the best for the latitudes and time of the year.

The sun's rays pass through the transparent cover and are absorbed by the black plate which becomes hot and heats the air above it. Since the air heater is inclined to the horizontal, the hot air, being less dense than the surrounding air, rises along the air heater and so air flow through the system is established. The temperature of the air leaving the collector depends on the length of the collector; the longer the collector the hotter will be the air at the collector exit. However, the air temperature is not a linear function of length since the heat losses increase as the temperature increases.

### **COST OF THE DRYER**

Apart from the transparent collector cover and the support legs, all other exposed parts of the dryer were made out of expensive metal sheets (eg galvanised iron sheets). This was intentionally done to ensure the long life of the dryers. The dryers are therefore expensive at approximately shs. 3000 (K£ 150).

An example of energy calculations showed that the energy required to dry 90kg of maize from 20% to 12.5% moisture content wet basis is about 24 MJ. This is equivalent to 0.52 kg of liquid oil (Calorific value = 10,400 calories per gram). Thus with a burning efficiency of 50% and drying efficiency of about 80%, about 1.3 kg of oil fuel would be required and this would cost in 1985 in Kenya £0.75 sterling. The cost of the dryer can therefore be recovered from oil savings in about 2 to 3 years if the dryer is used for at least 6 months each year (90 kg of maize dried every 3 days). With minor repairs, the dryer would normally last at least 6 years. This is a realistic economic advantage which indicates that this type of dryer will have a vital role to play in the rural development of farming techniques.

### **CONCLUSION**

One of the aims of this work was to simplify the design of an efficient solar crop dryer so that unskilled farmers can construct efficient dryers. But, dryer design remains a complex task which can only be accomplished by technically qualified people. It is therefore necessary to train the farmers to design and construct dryers while a simpler design approach is being sought.

The acceptance analysis of the crop dryers which have been built is still in progress. However, it is hoped that the farmers will accept them on the basis of the following advantages:

1. reduced crop losses.
2. safety from insects, rodents, domestic animals and theft.
3. controllable drying.
4. high quality product especially when climatic conditions make traditional drying method difficult to achieve without severe losses.
5. reduced amount of labour compared with traditional drying systems.
6. reduced land area than normally required for traditional sun drying.

### **ACKNOWLEDGEMENT**

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### **NOMENCLATURE**

- Cp = specific heat of air at constant pressure ( $J K_g^{-1} K^{-1}$ )
- G = solar radiation ( $W m^{-2}$ )
- H = vertical height (m)

$h$	=	corrective heat transfer coefficient ( $W m^{-2} K^{-1}$ )
$K$	=	thermal conductivity ( $W m^{-2} K^{-1}$ )
$m$	=	mass (kg)
$\dot{m}$	=	mass flowrate ( $kg s^{-1}$ )
$M$	=	per cent moisture content wet basis
$n$	=	number of perforated absorbing layers
$p$	=	pressure ( $N m^{-2}$ )
$Q$	=	heat flux ( $W m^{-2}$ )
$T$	=	temperature (K)
$U$	=	heat loss coefficient ( $W m^{-2} K^{-1}$ )
$u$	=	velocity ( $m s^{-1}$ )
$x$	=	distance along the collector (m)
$\alpha$	=	absorptivity of a surface
$\epsilon$	=	emmissivity of a surface
$\delta$	=	Stefan - Boltzmann constant = $5.67 \times 10^{-8} Wm^{-2} K^{-4}$
$\tau$	=	transmissivity of a material
$\theta$	=	angle of incidence (deg.)
$\rho$	=	density ( $kg m^{-3}$ )
$\eta$	=	efficiency
$S$	=	area per unit length

Subscripts:

$a$	=	air
$c$	=	collector/chimney
$d$	=	drying
$e$	=	exit/effective
$f$	=	final
$g$	=	transparent cover/grain

i	=	initial/inlet
l	=	layer
o	=	ambient
p	=	plate
s	=	sky/surrounding
w	=	wet grain
wa	=	water

FIGURE 1: Solar crop dryer

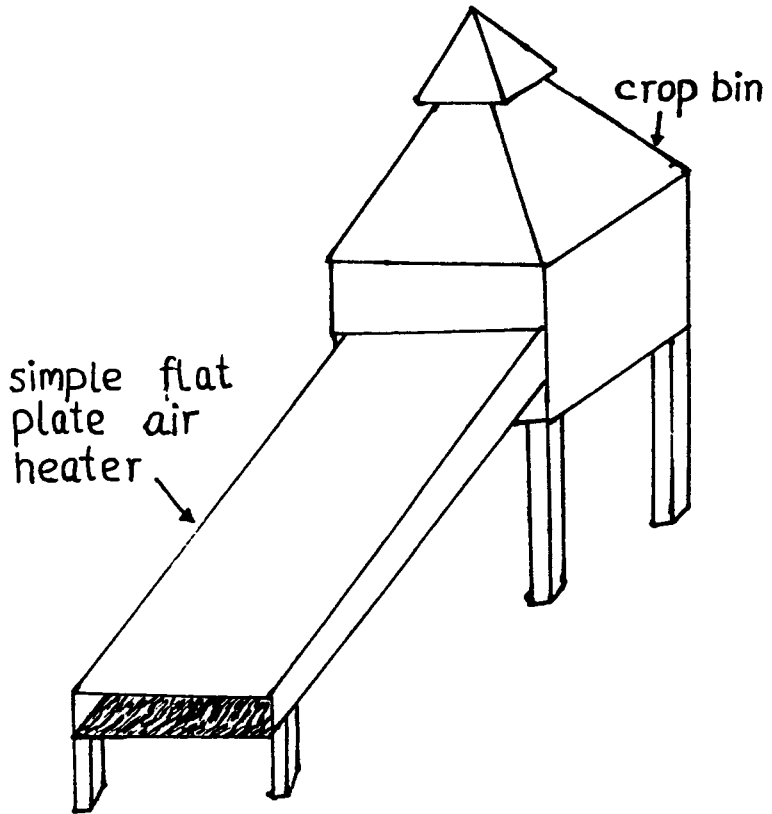
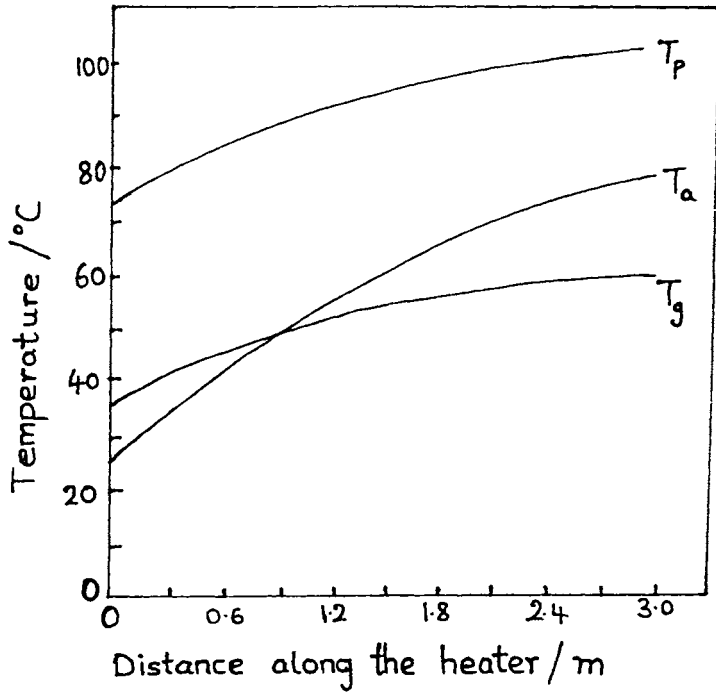


FIGURE 2: Model solution for a flat plate collector



**FIGURE 3: Multilayer solar air heater with perforated absorbing layers**

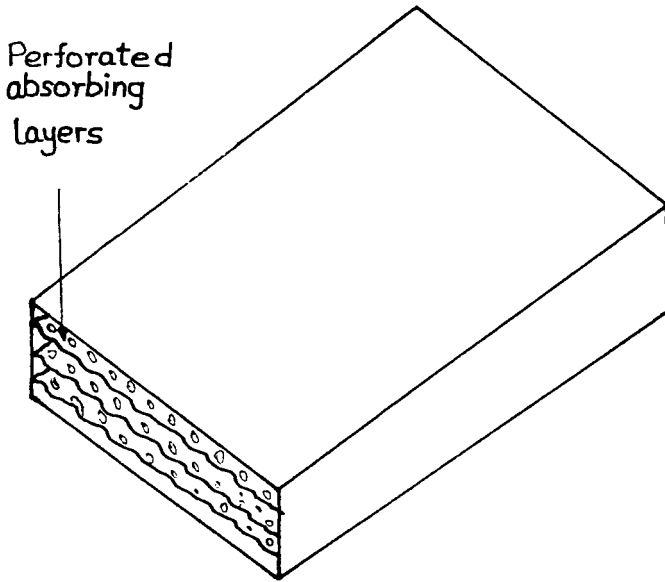
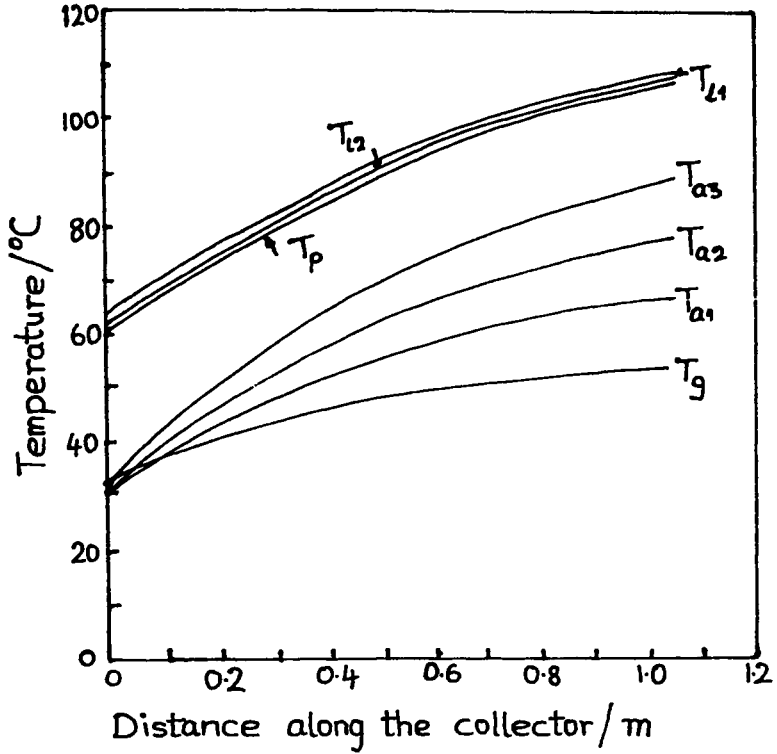


FIGURE 4: Model solution for multilayer solar air heater with two perforated absorbing layers



## **IMPROVING MASS FLOW RATES IN FREE CONVECTIVE DRYERS**

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### **ABSTRACT**

This paper presents the first results of specific experiments, conducted to design a low-cost solar dryer for small (less than 500 kgs) to medium (about 1000 kgs) scale rice farming operations. Data characterising weather conditions, and the operation and performance of the dryer configurations investigated, under no-load and load conditions are presented. Mass flow rates of drying air can be improved by: i. adequate sizing of chimney diameter and cabinet insulation; ii. proper design of the heated airflow path leading to a better output (dried grains per unit time) per unit of glazing area; and iii. replacing purchased imported elements of the dryer with comparatively inexpensive but superior locally available materials.

### **INTRODUCTION**

The spiralling cost of imported fuel and materials, the development and use of such dryers has become very unattractive. This paper reports the development of a solar crop dryer which is both free of the disadvantages of the traditional sun drying method and conservative in use of energy and materials. As a result of investigations reported here, two prototypes were designed. The performance of these prototypes on a no-load and load bases are compared with controls.

### **EXPERIMENTAL APPARATUS**

The solar crop dryer used for experimentation is shown schematically, in Figure 1. It consists of a solar collector, drying cabinet, and chimney. The air heater is constructed from galvanised steel sheet metal 0.16 cm thick, plywood, 1.2 cm thick and glazing 0.3 cm thick. The sheet metal, painted black, acts as the absorber plate. It is enclosed in a wooden frame heavily insulated with glasswool of 10 cm thickness. The air gap between the absorber plate and glass cover is 4 cm.

Air enters the collector, which is inclined at 20° to the horizontal, through the inlet at the lower end. Heated air from the collector flows into the drying cabinet through a heavily lagged throat.

The drying cabinet, made of plywood, has an area of 90 x 90 cm<sup>2</sup> and height of 70 cm. Up to three wooden racks inside it can carry sliding trays with wire mesh bases for loading the crops. All the cabinet panels are insulated with 7.5 cm thick bags filled with dry sawdust. There is a chimney of adjustable height and diameter.

Figure 1 shows the location of the copper-constantan thermocouples inside the dryer system. These are connected to a data acquisition system (deploying a temperature indicator, model 31671 Thermo electric) to monitor the temperatures. Temperature readings are correct to  $\pm 0.5^{\circ}\text{C}$ .

The flow rate (m<sup>3</sup>/s) through the dryer is monitored using an access port (Figure 1) located midway along the length of the chimney. This post is closed between

readings with a cork. The probe of the anemometer, TA 400 by Air Flow, measures the flowrate in a cross-section coplanar with the thermocouple location T<sup>7</sup>.

The solar radiation on the plane of the collector is measured using a solarimeter (solar 118, Enercorp). Humidity is measured by dry and wet bulb readings of a sling psychrometer. A wind anemometer measured wind speeds in the vicinity of the dryers under test.

## **EXPERIMENTAL PROCEDURES**

### **Experiment I**

Two similar dryers prototypes PI and PII were subjected to the same weather conditions to study the effect the changes in chimney diameter on the mass flow rate. PI with chimney diameter 15 cm was the control and PII, positioned in parallel to PI, was fitted with a different chimney diameter for each test.

### **Experiment II**

Two dryers (PI and PII) identical except that PI was not insulated were subjected to the same insolation levels.

### **Experiment III**

Two dryers PI and PII (Figure 2) were exposed to the same weather conditions for data acquisition. PI carried a tray of useable volume 87 cm x 56 cm x 12 cm mounted 22.5 cm from the cabinet floor. PII carried a similar tray of useable volume 77 cm x 55 cm x 12 cm having an air-flow slot of cross-sectional area 5 cm x 37 cm.

### **Experiment IV**

On-load data measurements for two dryers PI and PII, each with a tray, were compared with two control, C1 and C2, air drying methods under the same insolation levels. The tray in PI and PII was loaded with rice to a height of 6 cm. Control, C1, was a rice bed on the ground contained by a wooden frame to an area and height equivalent to that of the bed in PI. Control, C2, had the same quantity of rice, as in C1, spread thinly on the ground as in the traditional method.

Freshly cut rice was weighed and equal quantities placed in the dryers, PI, PII, C1 and C2. Initial samples were then taken for moisture content tests. Temperatures were recorded and samples of rice were taken from the dryers during the drying period at regular intervals of 30 minutes. The samples used for the moisture content determination were taken after mixing the rice in the dryers.

Each sample of rice was weighed and then placed in an oven, maintained at 110°C, for 24 hours. The weight of the dried rice was recorded and the moisture content on a dry basis established.

During all the experiments the insolation (I in W/m<sup>2</sup>, in the plane of the collector) the temperatures, and the air flow rate (m/s) at the measurement port 7 were recorded at 30 minute intervals. The wind speeds in the vicinity of the dryers were also monitored regularly.

## **RESULTS AND DISCUSSION**

### **The effect of diameter of chimney on mass flow rates in dryers under no-load**

The exhaust air flow rates (m/s) from the dryers were measured using the measurement port located at 7, Figure 1. These readings were transformed into corresponding mass flow rates under the following assumptions:

- a. The density of the air at 7 is a function of temperature and pressure at that position.
- b. Pressure at 7 is approximately equal to the ambient pressure, the length of ducting from the outlet of chimney to that position being very short.
- c. The outlet air is dry, thus the density of the air could be obtained from published data in the ASHRAE Handbook 1981.
- d. The equation of continuity applies.

Typical values for the mass flow rates obtained for various diameters compared against the diameter of 15 cm (Control) for different days (meteorological conditions) are shown in Figure 3. The general trend is that mass flow rate increases with increasing chimney diameter. This is consistent with the reasoning behind the glazing of chimneys to promote gains and inhibit losses. As the losses continue to rise with increasing diameter, the mass flow rate would tend to a peak value where the chimney losses match the gains. After this point no further gains in the mass flow rate should be observed. In the prototype understudy this was achieved with a 24 cm diameter chimney.

### **Effect of added insulation on dryer mass flow rates**

The insulated dryer (PII) had a superior mass flow rate profile, compared to that of PI (Figure 4). Insulation promotes the temperature difference between the hot column (heated airflow within the dryer) and the cold air column outside thus increasing the mass flow rate. The only limitation to its application would be costs and the thermal protection it offers the heated air output from collector without exposing the dryer mass flow rate to the transients of thermal mass and ambient meteorological conditions. Stable dryer operation is a design objective.

### **Effect of internal geometry of flow path on dryer mass flow rate**

The different internal geometry did not result in significantly different mass flow rates when not loaded with rice. When loaded there was a major difference in air mass flow rate depending on the internal flow path geometry. (Figure 5).

For the flow through bed design (PI) the drying air from collector is passed through the entire mass, across the surface of individual grains. For the flow-under-and-over bed design (PII) only the bottom and top layers of the rice bed are exposed to drying air. Moisture transfer from grain between these two layers would occur as a result of vapour migration between solid grains as opposed to vapour release from grains to heated air in the flow through bed configuration. So the mode of vapour transfer and flow path is different for PI and PII.

While more detailed tests are required to confirm the efficiency of the two designs, it is, however possible to make certain broad generalisations from the results, Figure 6. Starting from the initial moisture content of the freshly harvested rice the ranking of the dryers is CII, CI, PI and PII in that order. At no insolation, eg overnight, the rice absorbs moisture. The changes in moisture content are not smooth but there is an overall decrease in the level of this parameter with time, in agreement with work already reported by Bassey (1982).

### Significance of wind measurements

Meaningful readings of wind speed could not be obtained as any prevailing wind regime was very changeable - wind gusts of between 1-3 m/s only lasted for a few second and were few and far apart. Its effect is expected, however, to be twofold:

- a. promote improve flow rates when dryer is substantially aligned in its direction;
- b. encourage heat losses from the dryer. It is noted that the results of this wind effect can be uncomplementary.

### CONCLUSIONS

1. The analysis of performance of dryers is quite complex. An averaging technique relating the average values of insolation, heated air mass flow rate, temperature etc. is needed as a simple tool to analyse the interacting variables relating the dryer system to its load (drying rice). This would "iron out" the problem of induced irregularities due to thermal mass (insulation) and ambient meteorological conditions.
2. It is unrealistic to compare the traditional method of drying rice on a virtually unlimited area to other methods deploying a limited area. When drying area becomes a premium and alternatives (with superior thermal properties) to imported purchased materials are available the capital cost involved in dryer design and construction can be drastically reduced to match open air drying on a limited area. The result presented suggested this where it is difficult to separate PI, PII and CI in terms of performance.
3. Three evidently cheap ways of improving drying air mass flow rates in free convective dryers can be identified:
  - a. Optimising chimney diameter - the results of Experiment I.
  - b. Added insulation by switching over to cheaper locally available materials with better properties eg mudbricks, clay bricks and mortar for construction of drying cabinet.
  - c. Reducing the resistance to drying air flow by redesigning flow path.

### RECOMMENDATION

Research must be directed towards better and firmer control of dryer performance (drying air mass flow rate and temperature). The use of simple shutters to control the air inflows and exhaust should be explored.

### **ACKNOWLEDGEMENTS**

The author wishes to acknowledge the funding provided by the International Development Research Centre (IDRC Canada) under Project No. 3 - P - 83 - 0107. The invaluable comments of Dr M W Bassey and Mr A B A Akiwumi during the preparation of this paper deserve special mention. Finally the project personnel should be commended for their services during the data acquisition, and processing.

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Bassey M W (1982) Potential use and performance of indirect free convective solar crop dryers in Sierra Leone. Final Report, IDRC Research Project No. 3-8-78-0113, Department of Mechanical Engineering, University of Sierra Leone.

FIGURE 1: Diagram of dryer showing general features and location of measurements

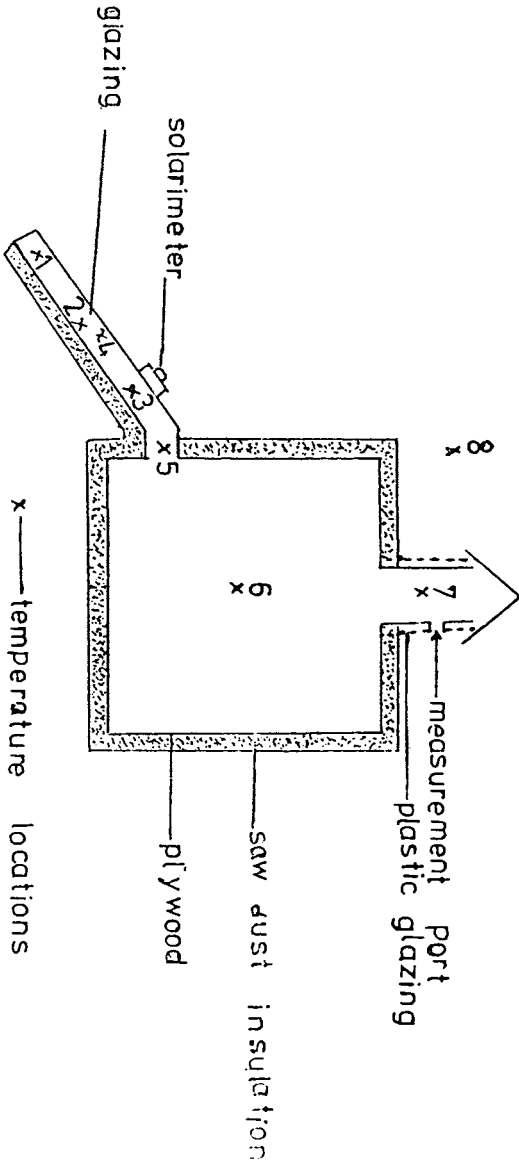
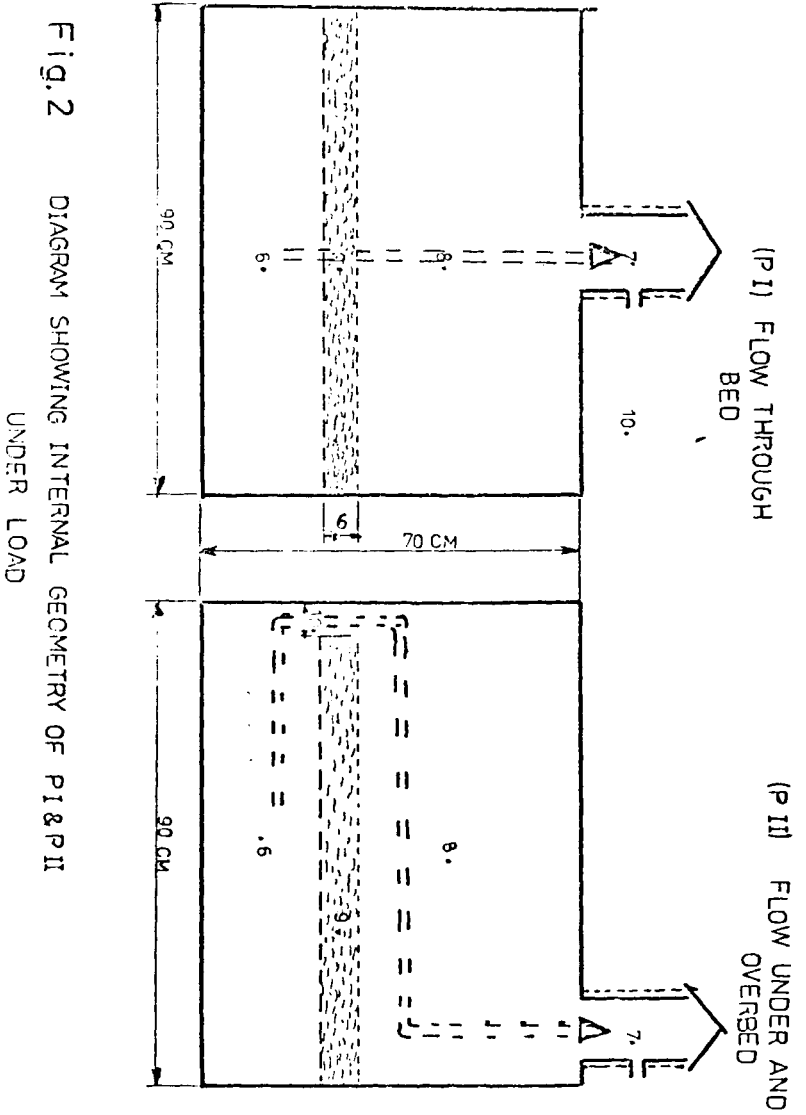
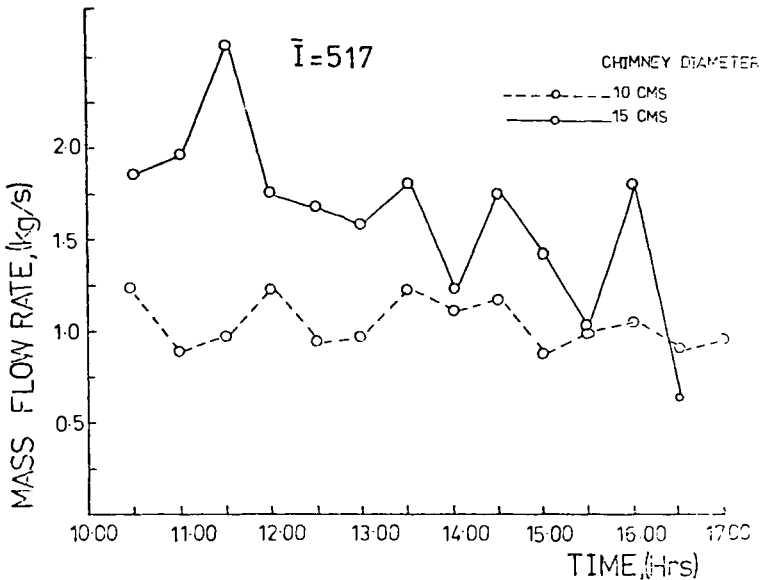
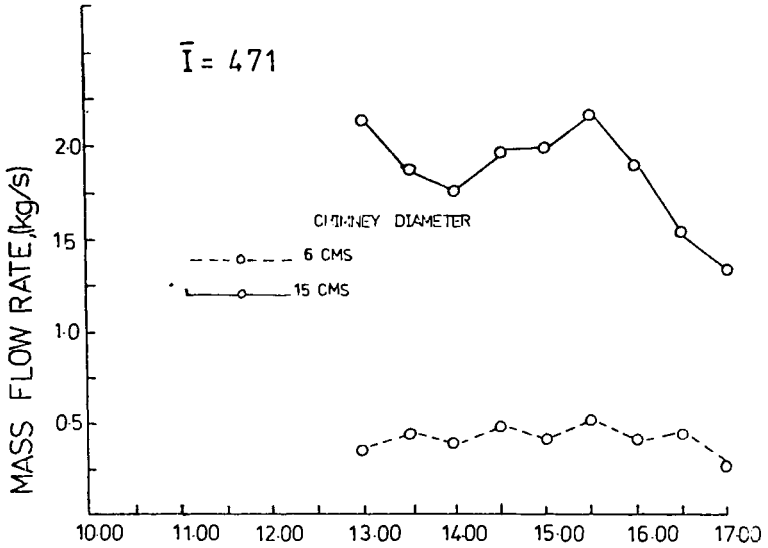


FIGURE 2: Diagram showing internal geometry of P I & P II under load



**FIGURE 3: Effect of chimney diameter on mass flow rates through dryer under no-load**



**FIGURE 4: Effect of insulating dryer cabinet on mass flow rates for no-load condition**

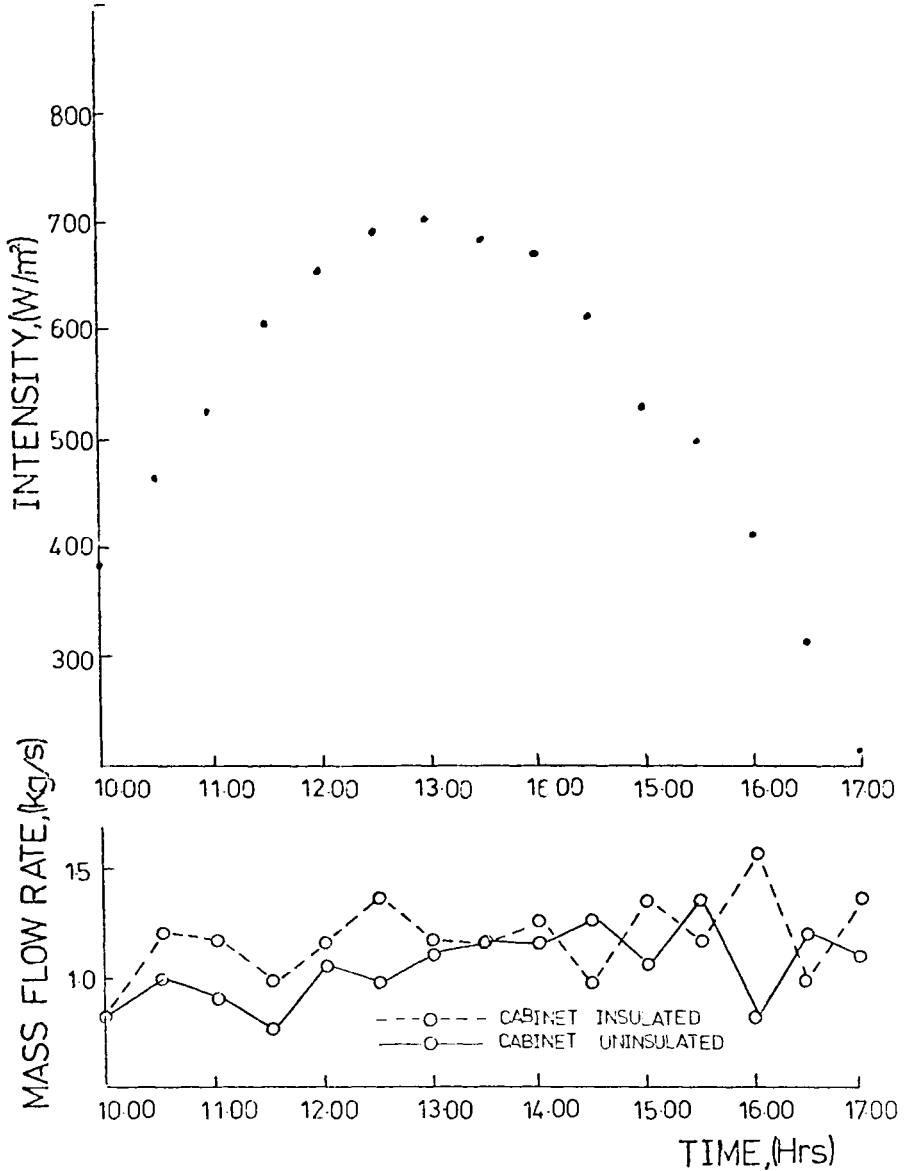


FIGURE 5: Comparison of mass flow rates for flow "through-bed" versus "flow-over-and-under bed" for loaded condition

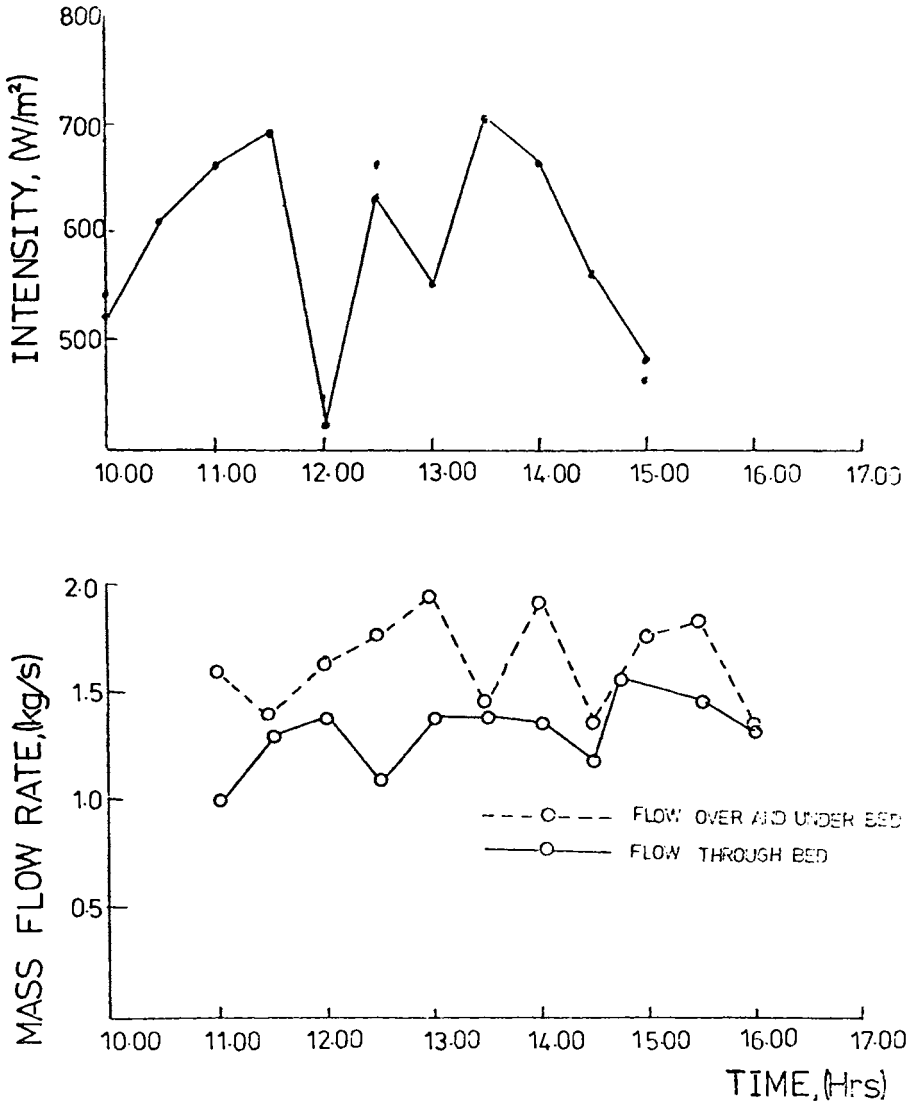
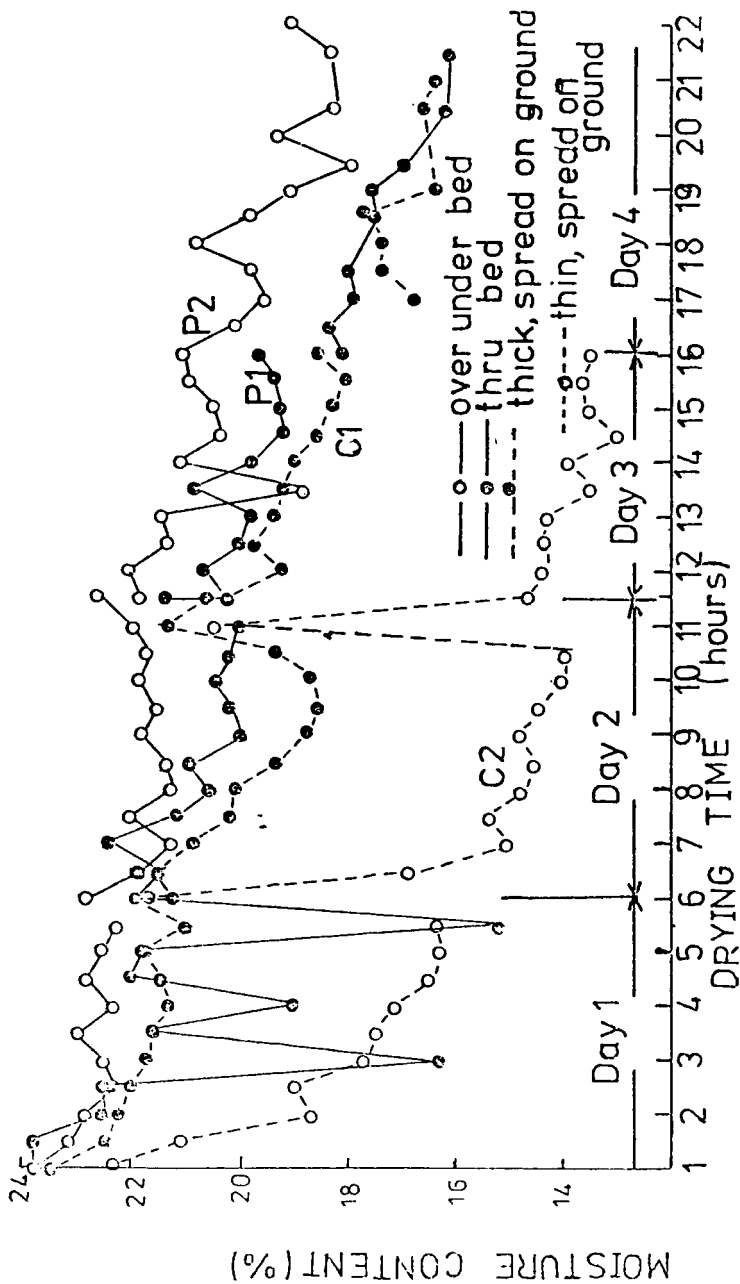


FIGURE 6: Drying curves for various conditions using rice



## **DEVELOPMENT OF A MULTICROP SOLAR DRYER FOR SMALL HOLDERS**

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### **ABSTRACT**

This paper describes the development of a solar crop dryer which will meet most of the requirements of the small holder. Heat storage can also be incorporated if necessary. It is cheap and uses locally available materials. The dryer is designed to operate effectively throughout the year in changing climatic conditions and is suitable for drying a range of crops including unshelled maize, red chillis, rice, groundnuts, ginger, turmeric, onions, garlic and various fruits.

### **INTRODUCTION**

The Government of Mauritius has set out production objectives for a number of crops in a policy of self-reliance (Table 1). All will need to be dried and stored. Some crops are only harvested at particular periods of the year, but the harvest times of all these crops is spread throughout the year (Table 1).

Large scale producers will normally use industrial drying processes. The 1200 small holders who will be called upon to contribute their share, will not be able to afford such processes. Most small holders farm only one fifth of a hectare and cultivate several crops. They are scattered widely across the island, and it is uneconomical and impractical to send their produce to a central dryer. It is, however, feasible for small holders in a particular area to form cooperatives or associations.

Sun-drying is currently the only practical approach for small holders. But there are several drawbacks, including the inability to achieve the recommended maximum safe moisture content. For example, sun dried maize can only reach a minimum of 14% moisture and necessitates further artificial drying to 12% at the rate of MR 100 per tonne.

This paper therefore describes the development of a solar dryer suitable for the needs of small holders and which can be used to dry all these crops and utilised throughout the year in Mauritius.

### **DESIGN AND CONSTRUCTION OF AN EXPERIMENTAL PROTOTYPE DRYER**

The design of the experimental prototype dryer was similar to the one developed by Exell (1980) for rice drying at the Asian Institute of Technology, Bangkok. However different materials were used. A sketch of the dryer is shown in Figure 1. The dryer was mounted on 200 mm concrete blocks, which in turn stood on a platform of concrete cement 50 mm thick. The platform and concrete blocks enclosed an insulating layer of air between the collector plate and ground.

The solar absorber was made of 22 gauge plain galvanised metal sheets coated with matt black paint. It had a collection area of 23 m<sup>2</sup>. It was fixed and supported by a horizontal framework of mild steel bars. Sixteen clear window glass panes (1.2 m x 0.95 m x 4 mm) fitted to a mild steel structure inclined at an angle of approximately 20° from the horizontal formed the cover of the collector system. The joint between the window frame and glass panes was

sealed with metal putty. The inlet vent (4.8 m x 0.1 m) was at the bottom of the collector.

The drying chamber housed four metal trays (1.2 m x 1.0 m x 0.3 m) with a bottom of fine galvanised wire mesh. The sides were made of a double layer of galvanised sheet metal and painted black. Two metal doors provided for the drying chamber were insulated with bitumen painted particle board. The chimney (0.2 m x 0.26 m and height 1 m) was made of sheet metal and painted black.

Initial drying tests were carried out by natural convection, but later the dryer incorporated a forced ventilating system provided by a centrifugal fan. The fan was powered by a 120 watt, 240V and 900 rpm motor capable of displacing 25 m<sup>3</sup> of air per minute. To obtain a uniform air flow over a solar collector two sheet metal baffles were installed inside a plenum of cross-sectional area, 0.025 m<sup>2</sup> (380 mm x 65 mm).

## RESULTS AND DISCUSSIONS OF EXPERIMENTAL PROTOTYPE

### Performance of solar collector

Design studies on various types of solar air heaters have been reported (Buelow, 1961; Close 1963; Whillier 1964; Bevil and Brandt 1968; and Niles et al. 1978). However, a simple method of calculating collector efficiency is to take the ratio of the net rate of useful heat energy collected per unit area to the amount of solar insolation:

$$\eta_c = \frac{Q_u}{AI}$$

where:  $\eta_c$  = collector efficiency;  $Q_u$  = useful heat collected, KJ hr<sup>-1</sup>;  
A = area of collector absorber, m<sup>2</sup>; and I = total insolation normal to the collector, KJ hr<sup>-1</sup>m<sup>-2</sup>.

By measuring the outlet collector temperature and ambient air inlet temperature, the useful heat output per unit area of collector is obtained from:

$$Q_u = GC_p (T_o - T_a)$$

where: G = mass flow rate of air per unit area of collector surface, kg hr<sup>-1</sup> m<sup>-2</sup>;  $C_p$  = specific heat of air, KJ kg<sup>-1</sup> °C<sup>-1</sup>;  $T_o$  = air temperature leaving collector °C; and  $T_a$  = ambient air temperature, °C.

Efficiency is therefore:

$$\eta_c = \frac{GC_p (T_o - T_a)}{I}$$

When empty the temperature rise of the drying chamber and absorber plate were respectively 35°C and 40°C, and the relative humidity was reduced by about 45% below that of ambient air. The average air velocity through the drying bed was 0.025 ms<sup>-1</sup>. Calculated solar collector efficiency, using the above equation, showed that it varied from a minimum of 34% to a maximum of 40%.

## **Performance of dryer**

### **Dryer operating by natural convection**

Several drying tests on batches of maize cobs and groundnuts weighing from 100 kg to 250 kg were carried out and the results showed a temperature rise of 30°C and a drying time averaging 6 days. The moisture content of both maize and groundnuts was reduced by 32% and 38% respectively to their required storage values of 12% and 9%.

Drying curves (A and B in Figure 2) show that after an initially high rate of drying, loss of moisture became progressively slower and then increased at the final stage of drying. A simple explanation of this drying pattern is that initially moisture at the surface of the grain was much easier to remove and as moisture from the interior of the grain moved to the surface the process became slower. During the final stage most of the moisture will have reached the surface where its removal was faster.

Drying rate is dependent upon both the rate of air flow over the grain and the temperature of the grain. Although high air temperatures were easily attained inside the drying chamber the air flow was relatively slow. This explains the rather long period needed to complete drying.

### **Dryer under forced ventilation**

Drying tests carried on maize cobs indicated that under forced ventilation there was a temperature rise of 25°C and the drying time was reduced at least 50%. Curve C in Figure 2 shows the drying pattern. For the first few hours the moisture content dropped by more than 7%, and this represented at least 50% of the moisture to be removed. For the next eight hours drying was partly affected by overcast periods and the moisture content was reduced by only 2%. In the final stage of drying seven hours were required to achieve the 12% moisture content.

The maize trials were carried out in summer. Trials on rice were also conducted in winter. The highest temperature rise recorded inside the dryer chamber was 20°C. Curve D in Figure 2 is the drying pattern for one of these trials. By the third day the moisture content had dropped from 30% to below the 14% required level.

## **System efficiency**

The system efficiency can be calculated using the following formula

$$\eta_d = \frac{WL}{I_s A}$$

where W = weight of moisture evaporated, kg; L = latent heat evaporation of water, KJ kg<sup>-1</sup>; I<sub>s</sub> = insolation on collector surface, KJ hr<sup>-1</sup> m<sup>-2</sup>; and A = Collector area, m<sup>2</sup>.

The results obtained from the drying experiments showed that with the dryer operating on natural convection the system efficiency ranged from 7% to 14%. When forced convection was employed a higher value varying from 11% to 18% was obtained.

## **Economics**

The construction cost of the prototype dryer was about MR 15,500 (valued at 1981) with maintenance costs of MR 200 per year. Maintenance includes cleaning of the glass panes, the interior of the drying chamber and the solar absorber to ensure maximum operating efficiency and repainting every four years.

Table 2 gives the annual operating cost calculated on the dryer operating for six months. It is assumed that the dryer would last for 15 years. A 10% charge for interest on capital investment is allowed to cover financing costs. The electrical energy required to power the fan is evaluated as 1 Kwh per day of operation at the rate of MR 1.40 per Kwh.

The cost of drying maize in an industrial fuel powered dryer is MR 50 per tonne for every per cent moisture content above 12%. If the average moisture content of crops sent for drying is 22%, then the charge is MR 500 per tonne. Table 3 is the cost benefit analysis for maize drying for different lengths of time of operation annually when an average of 4 days is taken to be the drying time for 400 kg of maize.

The investment cost could be covered from just over a year to about 4½ years depending on the period of utilisation of the dryer. In view of the relatively high investment cost, small holders may find it advantageous to join themselves in cooperatives or associations to benefit from such a dryer.

## **DEVELOPMENT OF AN IMPROVED PROTOTYPE**

### **Slope of collector**

It can be seen from Table 4 that the slope of the collector has to be varied constantly from  $-3^{\circ}$  to  $43^{\circ}$  through the year in order to get the maximum insolation. For four summer months the optimum angle is around  $1^{\circ}$  and for the four winter months about  $39^{\circ}$ . Only 2 months, namely March and September, require the average angle of  $20^{\circ}$ .

Since a multicrop dryer will be used throughout the year and a fixed collector is always preferable, the best angle has to be selected. It must be noted that any inclination put on the collector will normally result in a taller and therefore less practical and economical upward flow dryer, unless some excavation is made and/or a sloping site is available. Also the taller the dryer, the more vulnerable it is to cyclones.

If the average angle of  $20^{\circ}$  is used on a 5 m long collector, the drying chamber will have to be raised 1.7 m above ground. And to be practical this dryer will need extra accessories like a platform and staircases. This would increase further the already higher cost of a taller dryer. At this angle there will be a decrease of 6% in insolation in both summer and winter ie during 8 months of the year. Any advantages associated with such an angle is therefore not apparent.

In winter the insolation is lowest, and in addition, the air temperature, humidity and cloud cover are at their least favourable. It is therefore most important to use the optimum slope of  $39^{\circ}$  during this period, especially if May through August are the major drying months. In this case, there will be a loss from optimum of 23% in the summer months, although the loss can be offset by the

higher summer insolation and less severe climatic conditions. Such a collector slope will result in an extremely tall dryer with all its disadvantages. However a more practical and less expensive downward flow dryer (Figure 3) can be used.

A horizontal collector, on the other hand, offers the lowest cost and is most practical. Although on average it bears a reduction of 6% insolation throughout the year and 23% in winter, no reduction at all will occur in the four summer months. In any event, the decrease in insolation can be made up by increasing relatively the surface area of the horizontal collector. An enlarged collector to meet the requirements of the winter months will of course result in an over-design for all the other months. It must also be added that the glass cover, which is often parallel to the collector surface, will also cause some losses by reflection in winter. Therefore enlargement of the horizontal collector must also be considered to make up for the loss.

Thus, for a multicrop dryer to be used throughout the year, unless the site exceptionally lends itself to a sloping collector, an enlarged horizontal one should be preferred.

### **Optimisation of throughput**

Most crops take several days to dry to the appropriate moisture content, even in the best conditions. This means that a dryer will normally remain loaded with the same product for a number of days until drying is over. This will make the drying process costly for a number of reasons.

Firstly, each day the crop harvested has to be loaded in a separate dryer or set of dryers; thus several units will be needed for one crop, as the number of units needed will be equal to the number of days of drying. Further, if the drying is shortened by favourable conditions, no advantage can be taken of it. But if conditions become unfavourable, the harvest schedule will be upset. Secondly, the dryer or set of dryers must be enough to hold the daily harvest. Anything bigger or smaller will not be suitable. Also it implies that once decided, the volume harvested itself cannot be increased.

The problem can be overcome if the normal pick-up efficiency of 30% can be improved to as close as possible to 100%. Such a high performance can be achieved with a tier of trays. The air leaving a normal dryer is still fairly dry and can be utilised again. This principle was used to develop the new dryer.

Each set of one or more trays in the tier should have a capacity to contain the whole daily harvest, and therefore the number of sets required will equal the number of drying days. Thus at any given time all the trays will be fully loaded. Where the capacity of the set can only contain a fraction of the daily harvest, the number of dryers must be increased accordingly.

The capacity of the set of trays in fact will be limited by the outgoing relative humidity of air which should not exceed the water activity. For some products, a relative humidity of almost 100% leaving the drying chamber can be tolerated. Once the moisture absorption isotherm is known, a simple laboratory experiment using the inlet air conditions can be performed to determine the optimum total bed thickness and therefore the individual tray thickness and its capacity.

Initially the fresh product is loaded in the last set of trays at the outlet of the drying chamber, and everyday following it will be moved one step forward to the

inlet until the required number of drying days has been reached. Then the set of trays containing the adequately dried product is removed from the bottom of the tier (for an upward flow dryer), unloaded, refilled with fresh product and put back on the top and the whole cycle repeated. In these conditions, the daily throughput of the dryer or set of dryers will meet the demand of the daily harvest.

The number of trays in the tier can be increased or decreased depending on the drying conditions and the expected harvest.

### **Heat storage**

As the ambient temperature falls at night, the relative humidity of the air increases. When it has reached the water activity level, absorption of moisture in the product will occur. However, if the dryer is kept airtight at night, only minimal absorption of moisture from the enclosed air will occur.

More important, microbial activity will start above certain water activities and thus spoil the product. For example above a water activity of 0.80 molds will start to grow. It may therefore be essential for certain products when drying takes more than a day, to maintain a relative humidity of the air below 80% by preventing the temperature to fall too much. This can be achieved by maintaining the dryer airtight after sunset and switching on a supplementary artificial heater. The heater, presenting a number of drawbacks, can be avoided altogether if a heat storage system can be incorporated in the dryer.

A collector surface, having a high thermal inertia, serves as a heat store but unfortunately only during short cloudy period. To be useful the heat must be stored below the drying chamber and in sufficient quantities to maintain the warmth of enclosed air throughout the night.

An assembly of blackened concrete units (Figure 4) will serve the purpose: concrete has a high thermal inertia. The units must be streamlined to minimise the rate of heat absorption and to decrease the pressure drop and therefore the need to use a more powerful fan.

The downward flow dryer (Figure 3) can also be adapted to provide a heat storage system. Since the storage material is under and therefore after the drying chamber, it is the waste heat which is utilised. Therefore, as opposed to the upward flow dryer, it is a high rate of heat absorption which is desired. For this purpose, properly arranged blackened basalt boulders offering minimal pressure drop can be used. The results obtained with a prototype are shown in Figure 5.

### **A suitable multicrop dryer**

Figure 6 shows diagrammatically the features of a multiple crop dryer suitable for small holders. The glass covers are slightly inclined (1% gradient) to enable rainwater outside as well as condensation water inside to run off. Otherwise a glass cover parallel to the collector will result in a better heat transfer coefficient. The same steel framework and galvanised iron sheets can be used but the investment cost will be lower than that of the experimental prototype. Other cheaper substitute materials can be used to cut down the cost still more.

When crops like unshelled maize are to be dried only the two inclined trays are used. The cover of the drying chamber is first opened then the upper tray is removed and the bottom tray filled. Then the upper tray is replaced and filled in its turn. When drying is over the doors can be opened and the crops will immediately fall into the awaiting baskets. In certain cases, only the bottom tray need be used.

If crops like chillis or sliced fruit are to be dried, only the horizontal trays are used. In this case loading is done by opening doors of the drying chamber and sliding in the trays. These should fit exactly one on top of the other to ensure that air goes through the beds only.

For crops which can tolerate direct drying additional drying can be obtained from the glass cover of the drying chamber. Otherwise screening out with a piece of cardboard will be necessary.

### ACKNOWLEDGEMENTS

The work described in this paper forms part of the project within the African Energy Programme conceived and steered by the Commonwealth Science Council. The financial support given by the UK Overseas Development Administration is gratefully acknowledged. Thanks are due to the Ministry of Economic Planning and Development and to the University of Mauritius for providing facilities to carry out the work; to the Ministry of Agriculture, Fisheries and Natural Resources and to M S I R I for making available food crops for the drying tests. The valuable assistance provided by the technical staff of the University is greatly appreciated.

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**TABLE 1: Production objectives in the self-reliance policy and harvest times for key crops**

Crop	Production objectives 1987 (Tonnes)	Harvest times											
		Summer					Winter						
		Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Maize	15,000	X	X	X					X	X	X		
Groundnuts	2500			X	X	X							
Garlic	450								X	X	X	X	
Turmeric	230	X	X	X	X	X	X	X	X	X	X	X	X
Ginger	2000			X	X	X	X	X	X	X	X	X	X
Onions	4300									X	X	X	X
Beans & Peas	1600									X	X	X	X
Rice	6000						X	X	X				
Coffee	80												
Chillies	225	X	X	X	X	X	X	X	X	X	X	X	X

(Source: White Paper on Agricultural Diversification, Government of Mauritius)

**TABLE 2: Maintenance item**

Maintenance item	Cost/year MR
Depreciation of dryer	687
Interest on capital investment	1550
Annual maintenance cost	206
Electricity for 6 months	252
Total annual cost	2695

**TABLE 3: Cost benefit analysis of solar dryer**

<b>Period of utilisation (Months)</b>	<b>Annual operating cost (MR)</b>	<b>Returns (MR)</b>	<b>Profit (MR)</b>	<b>Payback period (Years)</b>
4	2611	6000	3389	4.57
6	2695	9000	6305	2.46
12	2947	18,000	15,053	1.03

**TABLE 4: Monthly variation of optimum slope angle (facing north)**

<b>Day of Month</b>	<b>Optimum Slope Angle</b>
14 November	1
10 December	-3
17 January	-1
16 February	7
<b>SUMMER AVERAGE</b>	<b>1</b>
15 May	39
11 June	43
17 July	41
16 August	33
<b>WINTER AVERAGE</b>	<b>39</b>
16 March	18
15 April	29
15 September	22
15 October	10
<b>AVERAGE</b>	<b>20</b>

FIGURE 1a: An experimental prototype

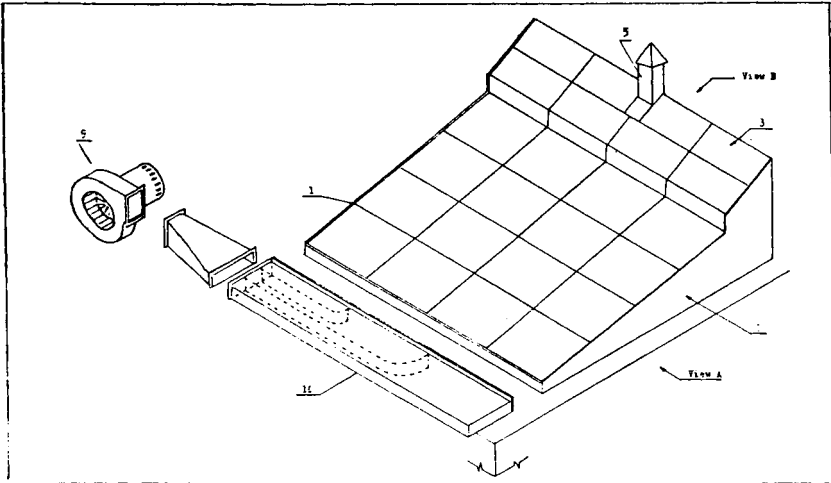
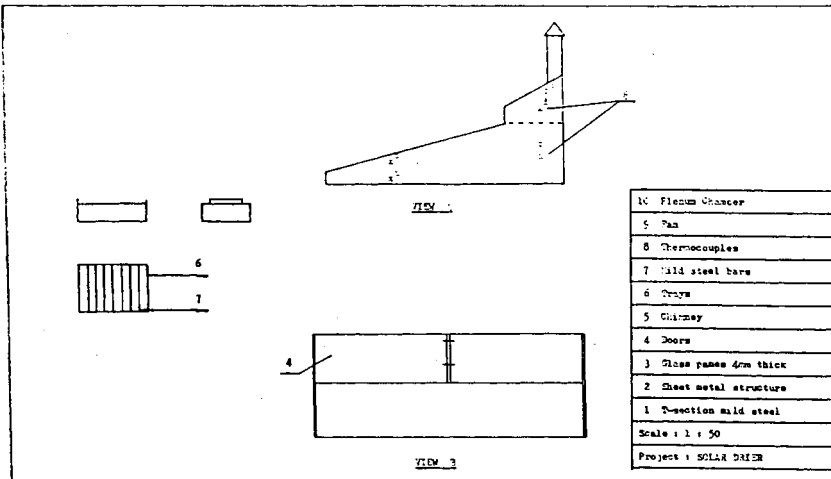


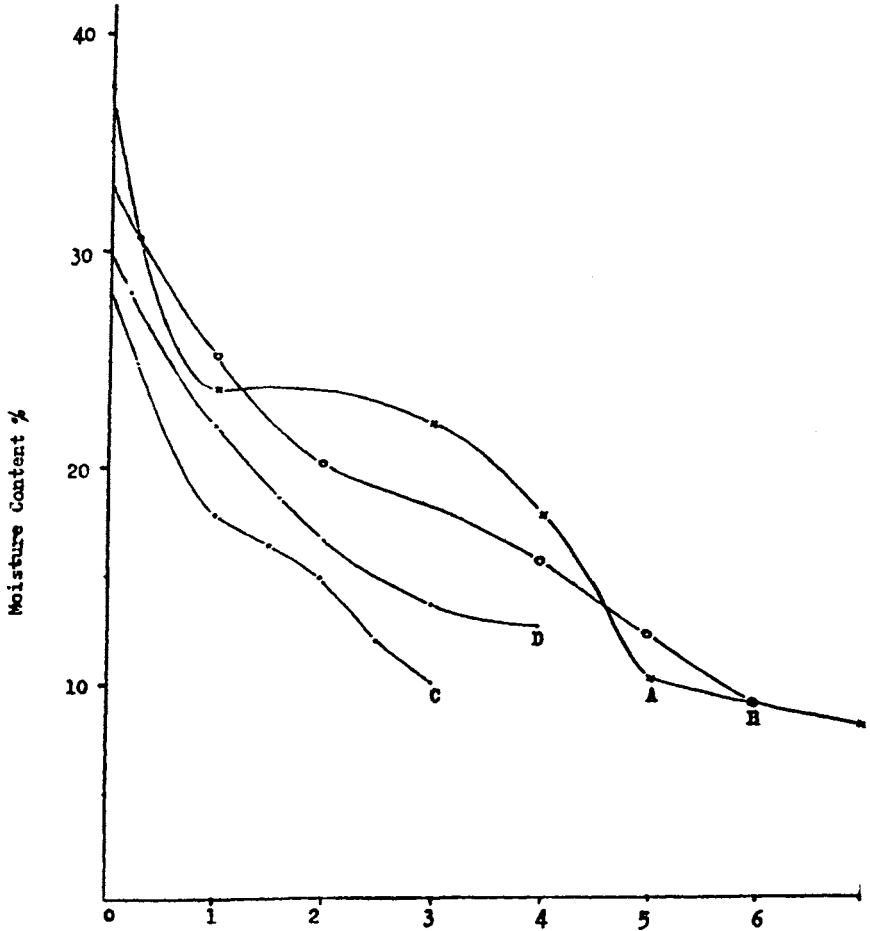
Figure 1b: An experimental prototype



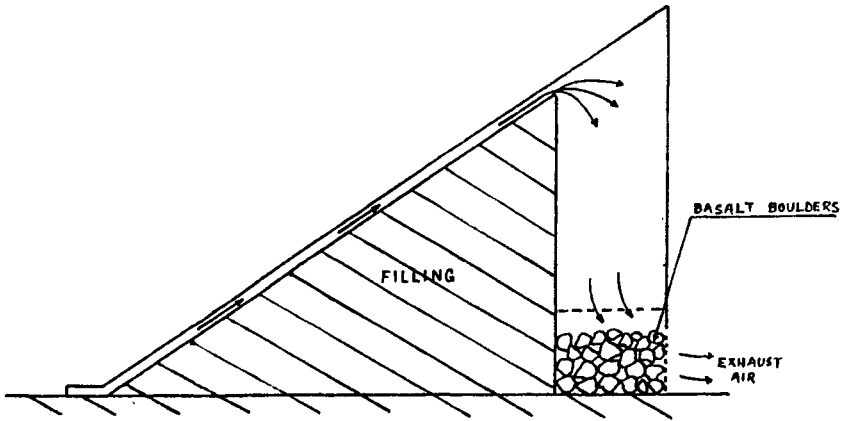
Scale 1:50

- 1 T-section mild steel
- 2 Sheet metal structure
- 3 Glass panes 4 mm thick
- 4 Doors
- 5 Chimney
- 6 Trays
- 7 Mild steel bars
- 8 Thermocouples
- 9 Fan
- 10 Plenum chamber

**FIGURE 2: Drying curves (A) and (B) for maize and ground nuts, both under natural convection; (C) and (D) for maize and rice, both under forced convection**



**FIGURE 3: Downward flow dryer with heat storage**



**FIGURE 4: Upward flow dryer with heat storage**

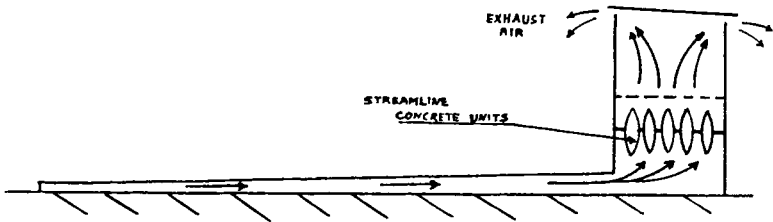


FIGURE 5a: Temperature with heat storage in downward flow dryer

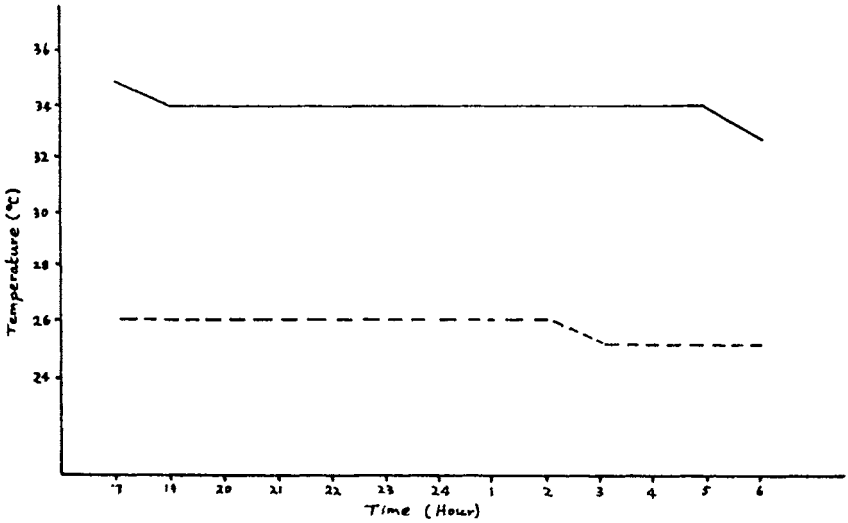


FIGURE 5b: Temperature without heat storage in downward flow dryer



FIGURE 6a: A suitable multicrop dryer

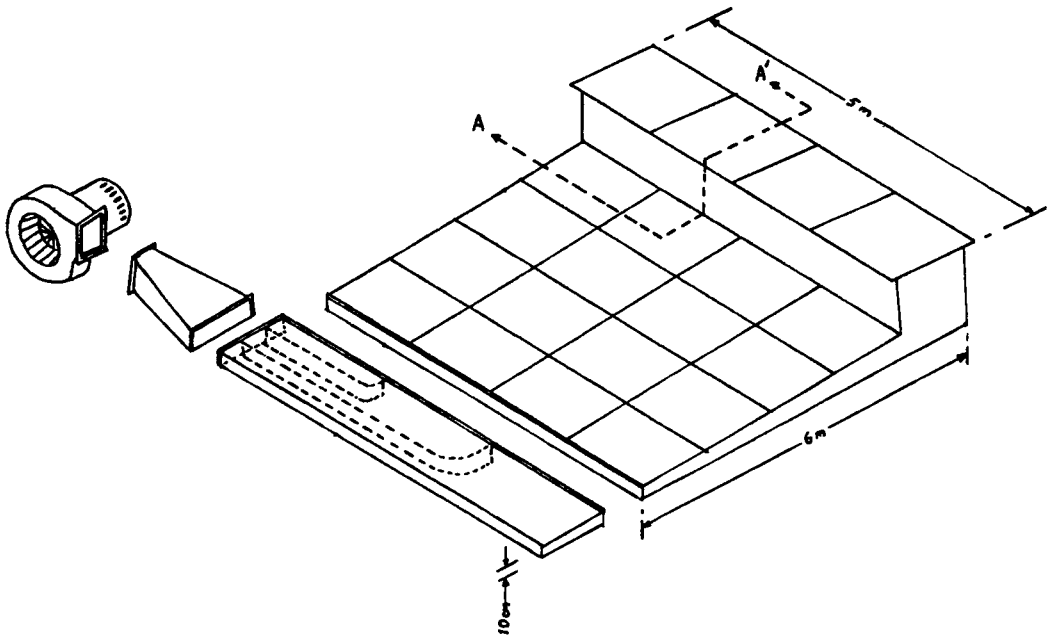
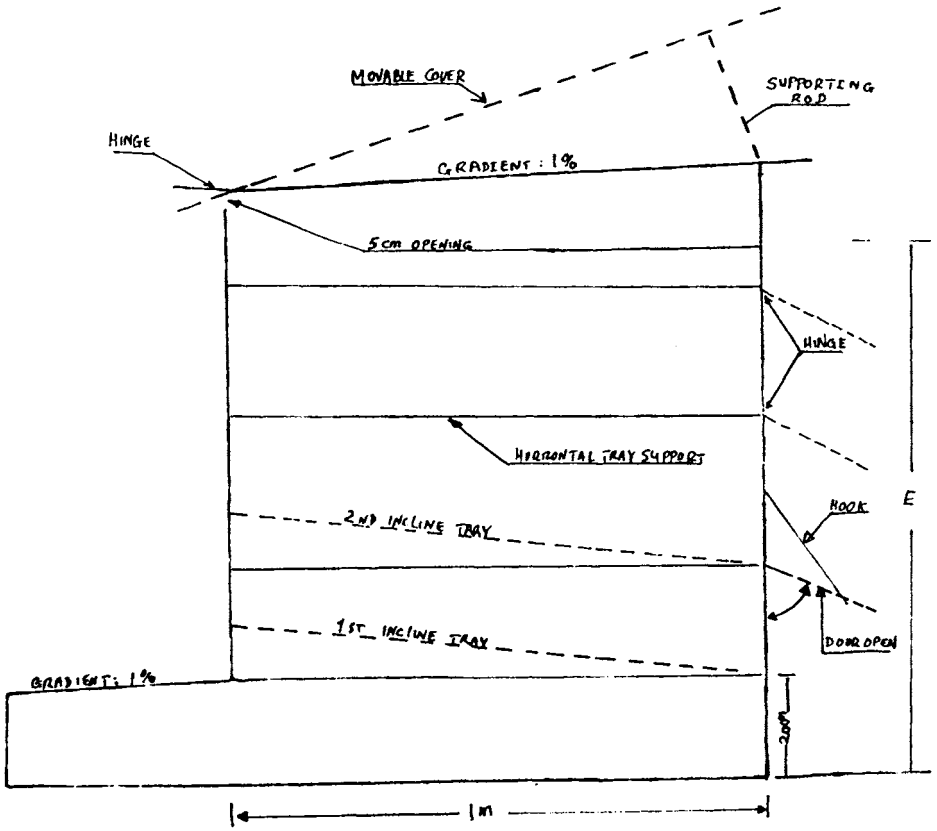


FIGURE 6b: Section AA' of multicrop dryer



**SOLAR DRYING OF TIMBER IN LIBERIA: DETERMINATION OF  
THE EFFICIENCY OF AN EXPERIMENTAL SOLAR DRYER BASED ON  
TEMPERATURE MEASUREMENTS**

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**ABSTRACT**

An experimental solar dryer designed and constructed at the Forest Products Research Laboratory of the University of Liberia is described. The dryer has a flat plate solar collector with transparent east and west facing walls. The collector section and the drying chamber are a single structure. Dryer temperatures and ambient temperatures are presented for the hours of 7:00 am through 7:00 pm for typical sunny and cloudy days. Results for sunny days were used to estimate the efficiency of the solar dryer. It was calculated that, on average, in this solar dryer it would take about 28 days to dry 8 m<sup>3</sup> of wood of 0.5 specific gravity from 55% to 15% moisture content.

**INTRODUCTION**

Traditionally, wood is dried by stacking lumber in an open yard. This is very inefficient in terms of drying time and quality of the dried product. Conventional dry kilns, powered by petroleum-based fuels or other fuels, are very efficient but are expensive to install and operate. Solar drying can offer an alternative to both air drying and conventional kiln drying. It is more efficient than air drying and less expensive than kiln drying.

Two basic types of solar kiln designs have been developed and used. In the first, the solar energy collector portion and the drying chamber are combined into a single unit. An alternative design has the collector and the drying chamber as separate units. Both designs have advantages and disadvantages. The combined system has a major advantage of being simple and relatively inexpensive. The major advantage of the separate system is that the collector area and orientation is usually free from the constraints imposed by the geometry of the drying chamber. Thus, the collector could be made large enough to optimise heat output and the drying chamber could be heavily insulated to reduce losses.

The purpose of this study was to design and construct an experimental solar wood dryer to assess solar drying possibilities in Liberia.

**Energy analysis of solar drying process**

In a typical solar dryer, solar radiation is collected to provide energy in the drying chamber that may be converted into useful work for drying. A simplified energy equation may be stated as:

$$U = E + L \quad (1)$$

where U is the total energy input into the system; E is the amount of energy available for the drying process; L is the total energy loss from the system.

In the case of a solar dryer, the total energy,  $U$ , is made up of the solar energy derived from the total radiation reaching the solar collector, the indirect radiation received from surrounding ground and objects, and radiation due to back reflections between the collector plate and the solar screen.

The amount of energy available for the drying process,  $E$ , is given by:

$$E = H_1 + H_2 + H_3 \quad (2)$$

$H_1$  is the energy required to heat the wood substance and is given by:

$$H_1 = W_t C_w (T_d - T_a) \quad (3)$$

where:  $W_t$  is the total weight of the wet wood (kg);  $C_w$  is the specific heat of wet wood (cals/g/°C);  $T_d$  is the dryer temperature °C; and  $T_a$  is the ambient temperature.

$H_2$  is the energy required to overcome hygroscopic forces, and it is dependent on heat of sorption of wood.

$H_3$  is the energy required for heating and vapourising the moisture removed from the wood, and it is given by:

$$H_3 = H_v W_r \quad (4)$$

where:  $H_v$  is the heat of vapourisation of water (cals/g); and  $W_r$  is the weight of water removed from the wood (kg).

The heat losses,  $L$ , are made up of

$$L = s + r + v + q \quad (5)$$

where:  $s$  is the unavailable energy due to absorption by the solar screen;  $r$  is the energy reflected by the solar screen;  $v$  is the energy loss through ventilation; and  $q$  is the energy loss through the wall, roof and floor of the kiln by both conduction, and conductive-convective mechanisms.

Thus for a given quantity of lumber being dried in a solar dryer, the energy that will be used for the drying process,  $E$ , will depend mainly on the difference between the operating temperature of the dryer and the corresponding outdoor temperature at any given time. The efficiency of a solar dryer is determined by what fraction of the total input energy is made available for the drying process. However, the value of  $E$  in equation 1 is almost constant for a given dryer design and kiln load. It is possible, however, to design a solar dryer which is capable of absorbing a greater amount of input energy,  $U$ , and reducing the heat losses,  $L$ , in which case the energy that will be made available for drying will be increased.

#### **THE EXPERIMENTAL SOLAR DRYER**

The solar dryer built at the Fendell Campus of the University of Liberia, is a wooden frame with a 3/8 inch plywood interior wall. The exterior wall is made of 26 gauge galvanised iron sheets. The dryer has the following dimensions:

Length (east to west)	5.1m
Width (north to south)	3.6m
Height (north wall)	2.7m
Height (south wall)	2.3m

The top half of both the east and west facing walls and the roof are made of 6mm thick glass sheets. The 75 x 150 cm roof panel is interconnected with moisture proof silka flex mastic and fitted into tongue and groove wooden strips. The 4.5 x 6.0m foundation of the dryer is concrete and one metre above the ground.

The heat absorber is made of black painted corrugated, 26 gauge galvanised sheets fastened to a wooden frame and suspended at about 30 cm below the main roof. A 15cm air passage gap is left between the heat absorber and the south wall. The distance between the heat absorber and the north wall is about 40 cm, which is large enough to facilitate the installation of fans to provide air circulation within the dryer.

All surfaces inside the dryer are painted black to improve the total heat absorbing capacity of the entire system. The total cost of materials for the construction of the dryer (excluding labour, supervision, etc.) was about \$3000.00.

#### **MEASUREMENTS OF DRYER TEMPERATURES**

The temperature inside and outside the dryer was measured every hour from 7:00 am through 7:00 pm over a 10 week period. This provided enough data for clear (sunny) and cloudy (over-cast) days.

#### **PRELIMINARY RESULTS**

Figures 1 and 2 show the average dryer temperatures with respect to the hour of the day, for a typical clear and over-cast day, respectively. The average rise in temperature above ambient temperatures, ranged from about 5°C to 22°C for clear (sunny) days. The average rise for cloudy days ranged from about 2°C to 16°C.

On sunny days the average dryer temperature during the day (7:00 am through 7:00 pm) was about 49°C and the average rise in temperature is about 20°C.

These results were used to determine the theoretical efficiency of the solar dryer and to estimate the expected rate and schedule of drying for typical hard wood species of Liberia.

#### **THERMAL ENERGY OUTPUT**

The magnitude of energy available for drying from a solar dryer can be determined on the basis of temperature rise in the dryer, that is, the differences between the dryer temperatures and the corresponding outdoor temperatures. If the dryer is considered as a typical heat exchanger, the thermal energy output from the system is given by:

$$Q = C_p \times M \times T \quad (6)$$

where:  $C_p$  is the specific heat of the medium, which in this case is air;  $M$  is the mass flow of air from the entire volume of the dryer;  $T$  is the operating temperature of the system.

The rise in temperatures takes into consideration heat losses from the system. Hence in calculating the thermal energy output from the dryer it is appropriate to use the value of the difference between the dryer temperature and the ambient temperature. Hence:

$$Q = C_p \times M \times (T_d - T_a) \quad (7)$$

where:  $T_d$  and  $T_a$  are dryer and ambient temperatures, respectively.

The volume of the solar dryer is approximately  $46\text{m}^3$ . The specific heat of air is  $0.24 \text{ cal/g} - ^\circ\text{C}$ . Density of air, , at a dryer operating temperature of about  $50^\circ\text{C}$ , is  $1.12 \times 10^{-3} \text{ g/cm}^3$ . The thermal energy output from the dryer for a typical sunny day between 7:00 am and 7:00 pm was thus calculated to be about 35,000 k cal.

### ENERGY REQUIRED TO DRY KILN LOAD OF LUMBER

The total energy required to dry a quantity of lumber that will constitute one load in the solar dryer can be determined by considering the various elements for heat consumption indicated in equation 2. The following data or assumptions must be considered.

- a. The capacity of the solar dryer for one inch lumber is  $3500 \text{ bd ft } 8\text{m}^3$ .
- b. It will be assumed that the average initial moisture content of the lumber is 55%, and that the wood could be dried to an average final moisture content of 15%.
- c. It will again be assumed that the average specific gravity of a typical Liberian hardwood species is about 0.50, based on green volume.
- d. It follows, therefore that the dry weight  $W_o$ , of  $8 \text{ m}^3$  of lumber is 4000 Kg and its wet weight,  $W_t$ , is about 6200 Kg.

The energy required to heat the wood substance ( $H_2$ ) is given by Equation 3. The energy required to overcome hygroscopic force in drying the wood from fibre saturation point to 15% moisture content is about 10 BTU/lb or 5.55 cal/gm. Thus

$$H_2 = 22,200 \text{ k cal}$$

The energy required for heating and vapourising the water removed from the wood is given by:

$$H_3 = H_v W_r$$

where:  $H_v$ , the latent heat of vapourisation, is about 572 cal/g at the operating temperature of  $50^\circ\text{C}$ ; and  $H_3 = 0.4 \times 4000 \times 572 = 915,200 \text{ k cal}$ .

The total energy required for drying the quantity of wood in the solar dryer is the sum of all the above.

$$E = H_1 + H_2 + H_3$$

$$E = 1,004,000 \text{ k cal.}$$

### CONCLUSIONS

Energy output from the solar dryer is about 35,000 k cal per day, on a clear sunny day. It would take approximately about 28 days to dry 8 m<sup>3</sup> of 25mm thick lumber, of an average initial moisture content of 55% to an average moisture content of 15% in the solar dryer.

This estimate is based on temperature measurements for clear (sunny) days only. For cloudy days the thermal energy output from the dryer would be much less. Preliminary drying experiments conducted with one inch boards of Niangon (*Tarrietia utilis*, Sprague) indicated that such boards could be dried in the solar dryer from an average moisture content of about 60% to 15% in 35 days. It takes about 90 days to dry similar boards of the same species in the open air under a shed. And in an electric heated dry kiln of 1 m<sup>3</sup> capacity about 14 days.

From these preliminary results it appears that solar drying is much more efficient than air drying. Even though solar drying did not appear to be as efficient as the electrically heated dry kiln, the cost of solar drying is much less than kiln drying.

However, these experiments need to be repeated to obtain more reliable data of both the efficiency and economic viability of the solar drying process.

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**FIGURE 1: Average Temperatures Versus Time of Day for Clear (Sunny) Days**

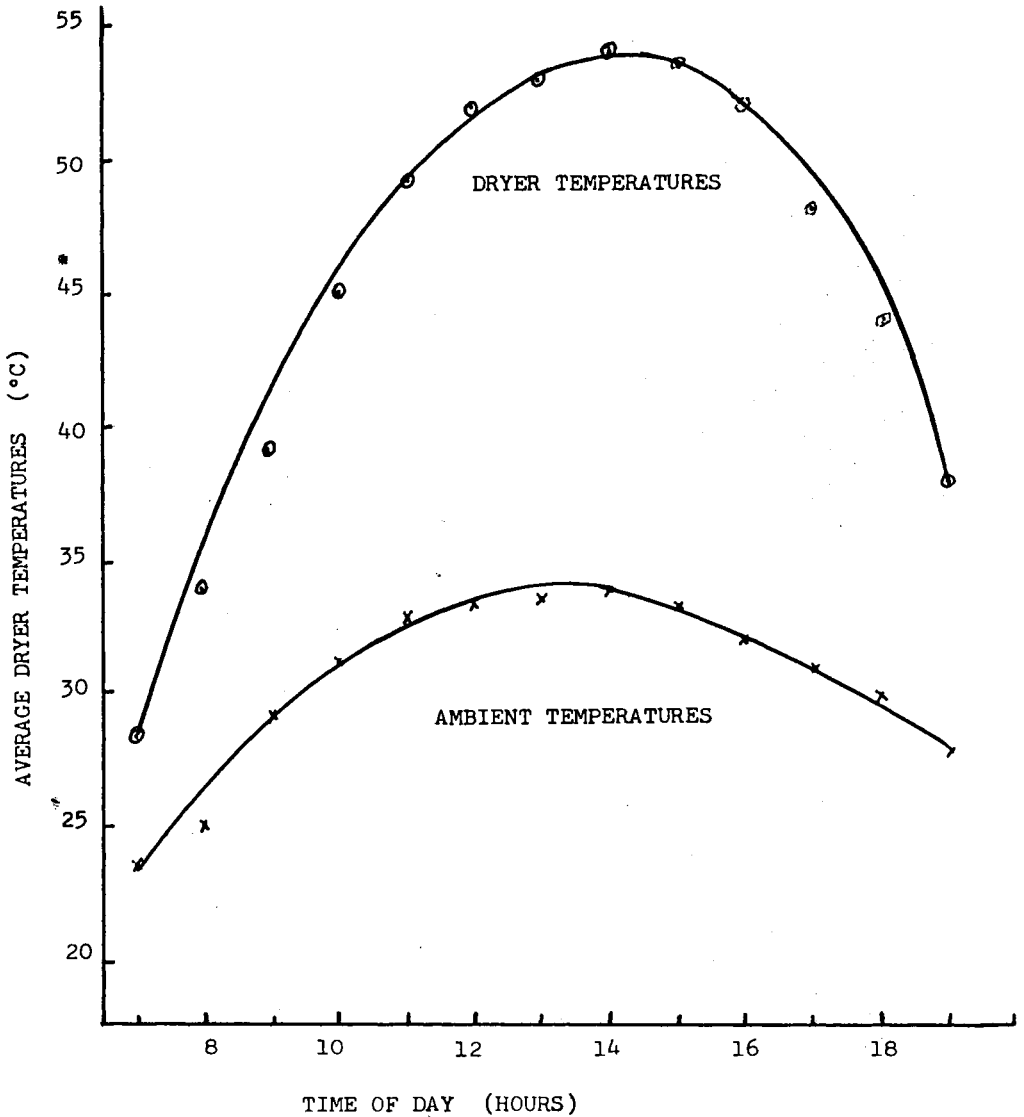
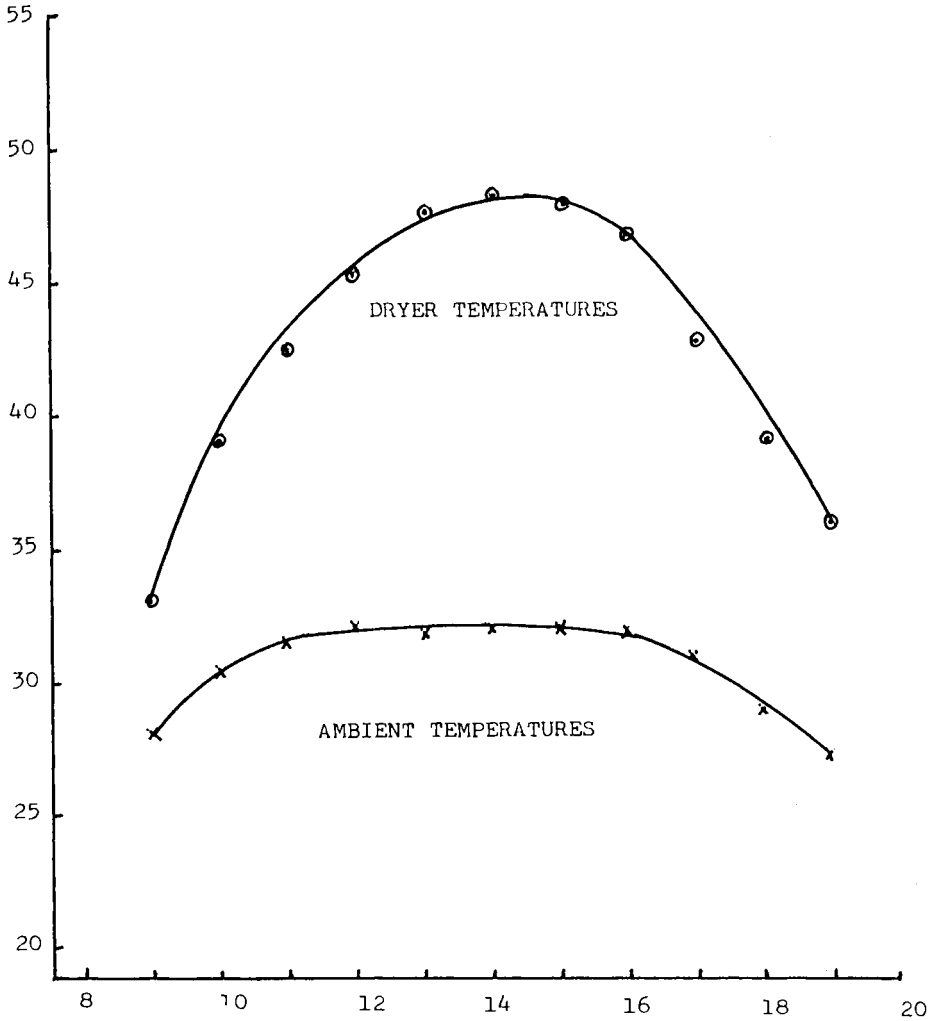


FIGURE 2: Average Temperatures Versus Time of Day for Cloudy Days



## **FIELD TEST OF A TWO TON CAPACITY MAIZE SOLAR DRYER**

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### **ABSTRACT**

The design and field testing of a two ton capacity maize solar dryer are described. Successful drying was achieved but natural convection reduced the energy efficiency. It is concluded that the seasonal short-term utilisation of the dryer does not justify the financial investment.

### **INTRODUCTION**

Many papers deal with theoretical studies, modelling and laboratory work on solar drying (Kranzier 1975, Harris 1976, Midwest Plan Service 1980, Muthweerappan 1978). During the last 6 years our laboratory has designed and tested a number of experimental scale solar dryers. These include 5 kg capacity solar dryers (for wood) and 250 kg capacity dryers for maize, cassava, sea fish, and okra. Three solar dryers of 2.5 m<sup>3</sup> capacity have now been built for cooperative farmers. Their design and construction details, and the results of a field test are described below.

### **DESIGN AND CONSTRUCTION**

The solar dryer was designed for crops of about 20% water content to be reduced to 13% according to regional climatic data and governmental regulation.

It is of a mixed type of design with a heat storage system. Solar energy is collected on a glazed area of 81 m<sup>2</sup>; 27 m<sup>2</sup> on the roof (D<sub>1</sub>, D<sub>2</sub>) and 54 m<sup>2</sup> for the indirect heat collection process (C<sub>1</sub>, C<sub>2</sub>) (Figure 1). The area for indirect collection is twice as big as that for collecting solar energy directly so that the temperature in the drying cabinet is kept higher than the ambient temperature even at night.

Because the latitude of the location is low (6° - 7°N), a symmetrical profile is adopted to reduce heat losses by the side walls and to allow easy loading and unloading of the crops. The walls are insulated by a 10cm thick layer of cotton. Two drying trays, 1.20 m by 12 m, are separated by a corridor of 1 m in width. Below each tray, a rock pile storage system of 0.4 m thickness helps to keep the relative humidity lower than 60% even with an ambient value of 100%. The thickness of the rock pile is calculated according to the time of heat propagation from the bottom to the top of the bed. The diameter of the rocks is about 5 cm in order to allow easy circulation of the hot air.

The lower air collectors have a 0.1m thick layer of rocks as absorber, heat exchanger and inlet air filter. The resultant higher heat exchanging area compensates for the thermal inertia of the rocks. These rocks are commonly used and available in rural villages. The rock layer is painted black and supported by a fine wire mesh. The inlet air has to cross it before flowing into the drying cabinet through the storage bed.

In the symmetric profile, a row of collectors faces south and a second north (Figure 2).

## **RESULTS OF FIELDS TRIALS**

Field trials were conducted with two tons of maize in a layer of 6 to 8cm thickness. Figure 3 shows the temperatures and relative humidity within the dryer during 5 days operation. Mean daily insolation was 4 kwh/m<sup>2</sup>/day. The temperature inside the dryer ranged from 30°C to 58°C as the ambient temperature increased from 21°C to 35°C during a day. The air temperature in the drying cabinet is about 16°C higher than the ambient temperature and is sufficient for grain drying. The relative humidity varied from 18% to 60% against 60% to 100% for the ambient air.

The air flow was very weak but the moisture content dropped from 20% to 14% in the first day (Table 1) with an overall energy efficiency of 15%. The second day reduces the moisture to 13% followed by the usual fluctuation around 12% of the next two days in good agreement with the general equilibrium curve of maize and relative humidity of the ambient air (Figure 4).

## **CONCLUSION**

Maize grain can be successfully dried in the solar dryer in two days instead of four days in the traditional air drying process. A drop in moisture content from 20% to 14% is achieved in one day. This performance can be further improved by increasing the air flow to 3m<sup>3</sup>/min for one m<sup>2</sup> of maize. As in an earlier prototype, PVC ducts can be installed through the storage bed to be opened on the first day and closed later on.

Local material and manpower were used but the cost (\$10,000) remains high comparatively to the 4 to 6 weeks of utilisation during the year.

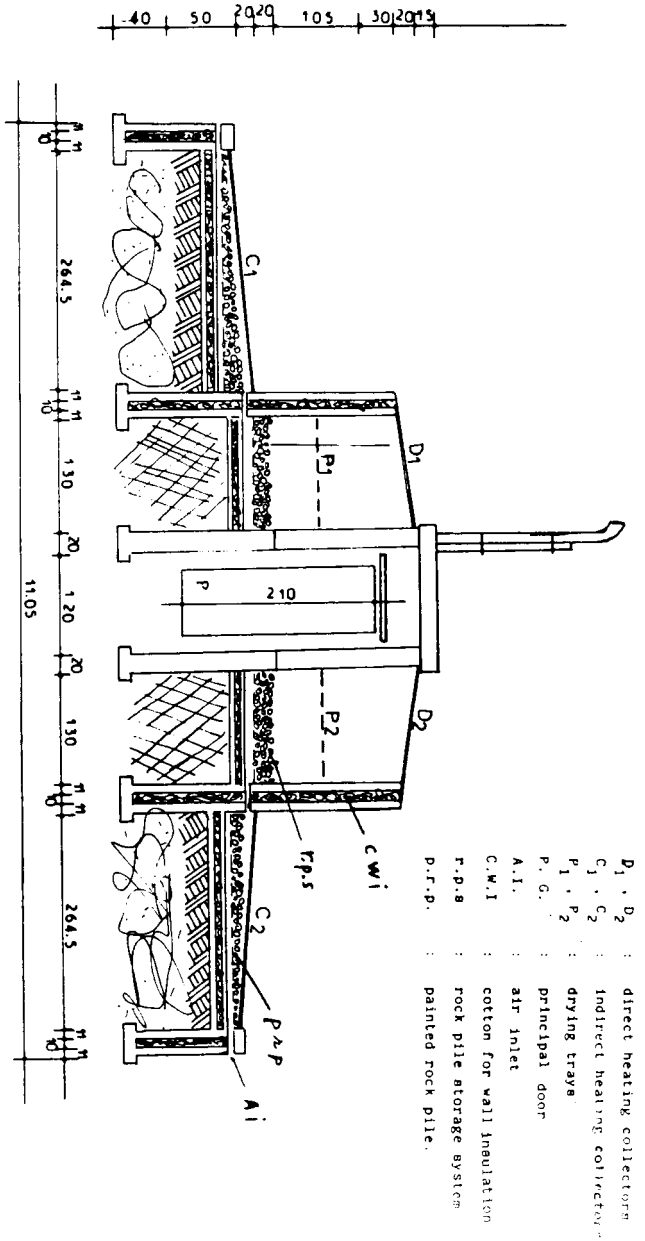
## **ACKNOWLEDGEMENT**

This work was supported by a USAID grant no. 698 0407 09/79.

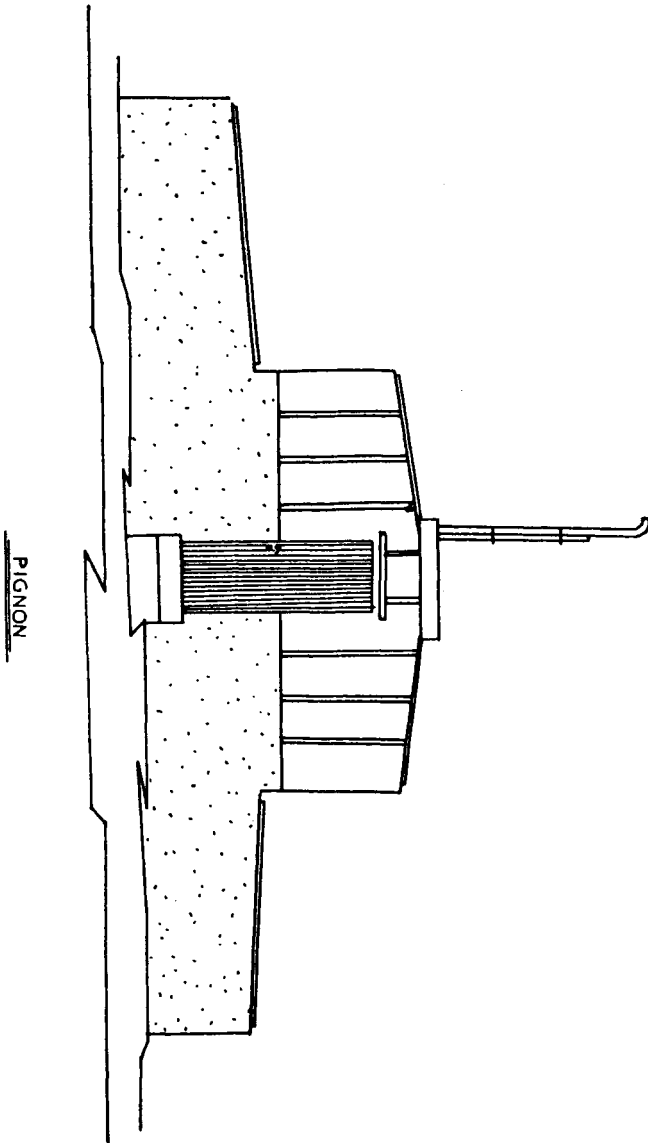
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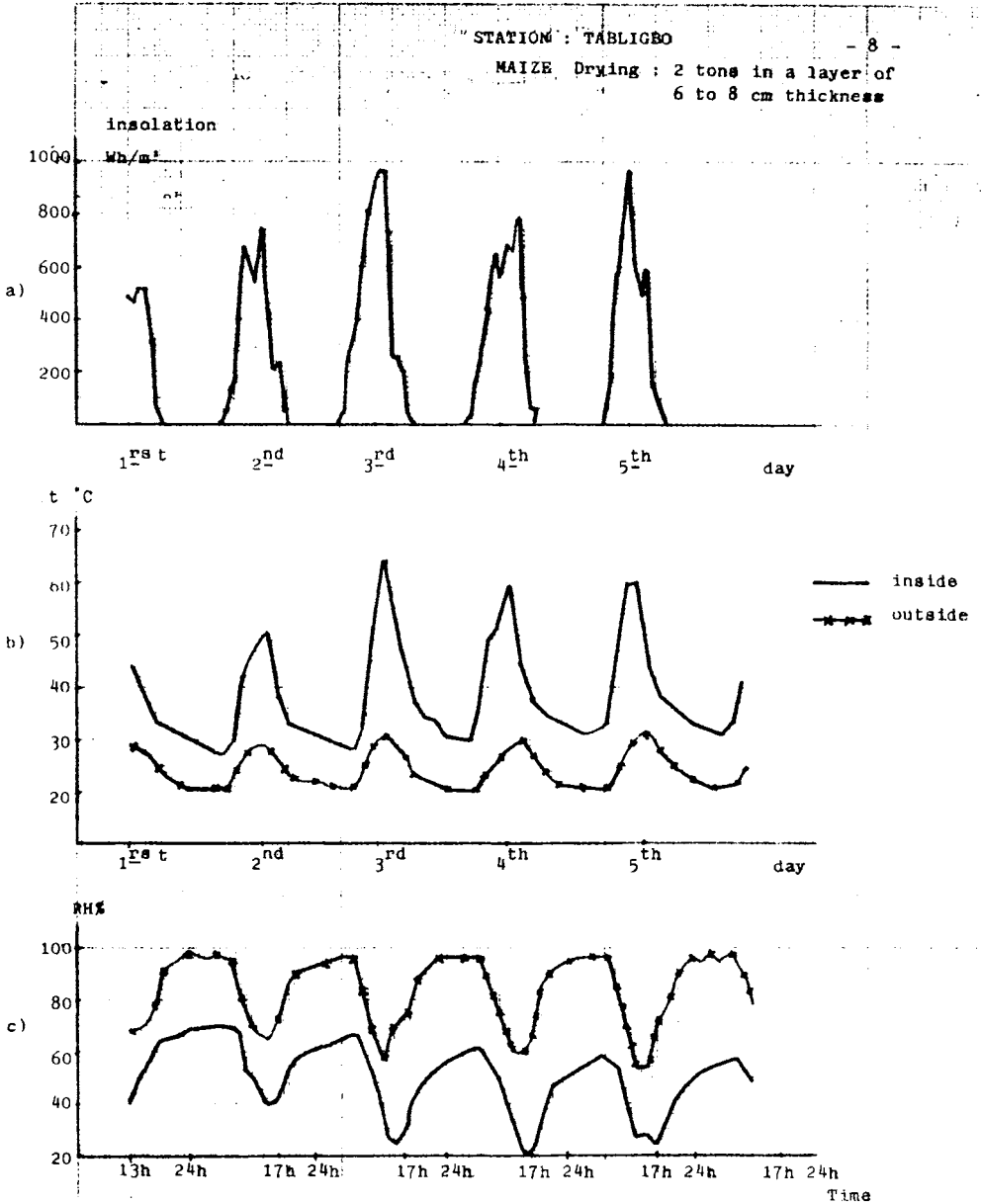
FIGURE 1: Cross-sectional diagram of a two ton capacity maize solar crop dryer



**FIGURE 2: Symmetric plan of two ton capacity solar drop dryer for maize**



**FIGURE 3: Temperatures and relative humidity within solar crop dryer during 5 days operation and the insolation, ambient air temperature and relative humidity**

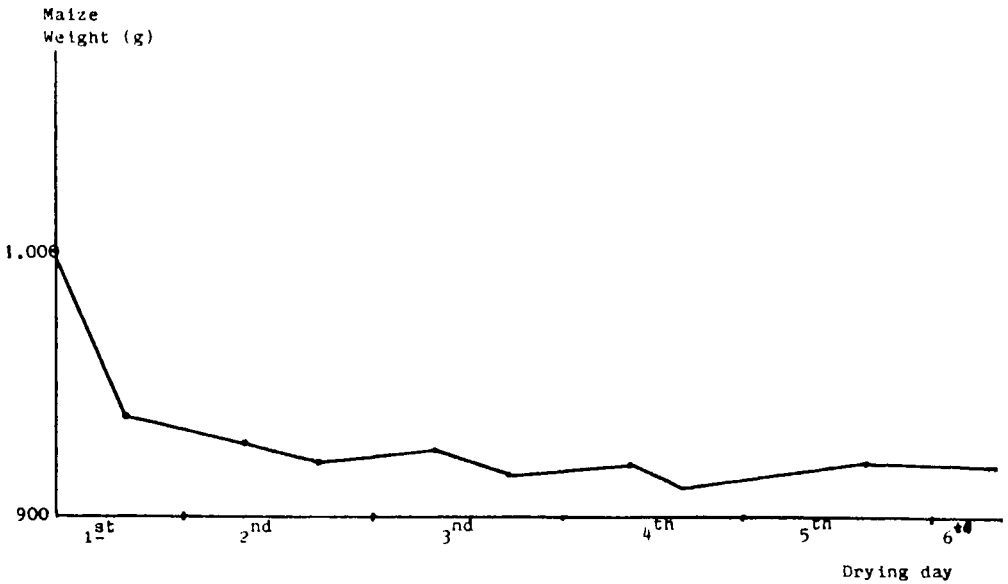


**TABLE 1: Moisture content of maize durin uring drying time**

	Initial moisture	Drying Time (days)					
		1	2	3	4	5	6
$\frac{Me}{Mo}$	20%	14%	13.2%	12%	11.6%	12.1%	12.6%

Me : water weight; Mo : maize initial weight

**FIGURE 4: Maize dehydration curve**



## **EXPERIMENTS ON AN OPEN-CYCLE SOLAR REGENERATED DESICCANT BED GRAIN COOLING SYSTEM**

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### **ABSTRACT**

Grain can be protected from insect attack, and have its properties preserved by cooling it to temperatures around 15°C. In temperate climates, grain can be cooled effectively by aerating it with cool atmospheric air, but the degree of cooling is limited by the heat of absorption released as the grain absorbs moisture from the air. In tropical climates this problem is compounded by the generally high ambient dry-bulb temperatures. Lower grain temperatures may be achieved by reducing the enthalpy of the aeration air. Experiments on a single-stage and a two-stage open-cycle solar regenerated desiccant bed grain cooling system that reduces the enthalpy of the aeration air are described. The rate of energy loss from the device was about 20 times that of the electrical energy supplied to the system. This compares favourably with vapour compression systems.

### **INTRODUCTION**

Cereal grains are harvested seasonally, yet they are consumed continually, and for this reason they have to be stored. During storage, severe losses may occur because of attack by insect pests, infestation by moulds and mites, and predation by birds and rodents. In addition, grains that are stored for prolonged periods may suffer a reduction in quality as indicated by a loss of seed germination, baking and milling characteristics, changes in colour and so on. Chemical insecticides applied to improperly stored grains are likely to lose their toxicity very rapidly. Cooling grain, either as an adjunct to chemical pesticide treatment, or alone improves the long-term storage of grain (Thorpe 1980).

The simplest method of cooling bulk stored grain is by blowing through it cool atmospheric air. The effectiveness of natural aeration is limited by the fact that the periphery of the grain store is not cooled sufficiently to control insect pests. Furthermore, the hygroscopic nature of cereal grains generally prevents the grain being cooled to ambient temperature, for reasons described below. Both of these drawbacks of natural aeration may be overcome by refrigerated aeration (Elder *et al.* 1983). This requires the grain store to be thermally insulated and the aeration air re-cycled through mechanical refrigeration units. This process involves more capital expenditure than natural aeration and it is energetically more demanding.

This paper describes an open-cycle, stage-wise solar regenerated desiccant bed grain cooling system, which embodies simple technology and has a very low energy consumption. The system enables grain temperatures lower than ambient to be attained.

## **THE COOLING MECHANISM**

The passage of air through a packed bed of hygroscopic material such as cereal grains involves both heat and moisture transfer. This has profound consequences on the rate at which temperature waves move through the porous matrix and on the temperatures attained. In this paper we shall discuss only the bulk storage of grains, although the benefits conferred by cooling on the preservation of grain are independent of storage method.

Bulk grain may be cooled by blowing through it air of the appropriate conditions. Grain interacts with the moisture in the aeration (cooling) air and under normal storage conditions most of the grain will not cool to the air inlet temperature. The heat and moisture transfer phenomena governing grain cooling have been elucidated by Banks (1972) and Suntherland *et al.* (1971). One of the principal conclusions arising from their work is that the temperature to which most of the grain will cool is dependent on the initial grain moisture content and the wet-bulb temperature of the aeration air.

Using properties of the air-grain-water system presented by Sutherland *et al.* (1971), we find that aeration air at 15°C and 50% relative humidity (rh) will cool most of an initially 12% moisture content (mc) grain bulk at 30°C to about 15°C. If the grain were initially 9% mc it would cool to about 23°C. If the aeration air is 15°C but 90% relative rh the corresponding temperatures to which most of the initially 12% and 9% stored grain would cool are about 19°C and 27°C respectively.

The speed at which cooling waves move through grain is about  $2 \times 10^{-3}$  times the superficial air velocity. A second cooling wave also travels through the grain during which the grain becomes in hygroscopic equilibrium with the aeration air. The speed of the second wave is about  $5 \times 10^{-5}$  that of the superficial air velocity.

## **A DESICCANT BED GRAIN COOLING SYSTEM**

From the above it may be inferred that the effectiveness of grain cooling is enhanced by reducing the enthalpy of the aeration air. An effective method of doing this is to isothermally reduce ambient air humidity. This can be achieved by blowing ambient air at night through a narrow bed of desiccant material so the heat of sorption can be readily dissipated to atmosphere (Thorpe 1981). The desiccant becomes wet, but it can be dried out during the day by means of solar radiation falling on the desiccant bed. This method is effective, but the narrowness of the desiccant bed of porous medium results in a high pressure drop across the system.

A method of overcoming the pressure drop is to carry out the drying and cooling of the air in a stage-wise process. The principal elements of one such system is shown in Figure 1. During the air drying and cooling process night air from the aeration enters the first heat exchanger, HE1, and some of the heat of compression is lost to atmosphere by convection and radiation to the night sky. The cool, humid air then enters desiccant bed, DB1, where it is dried isenthalpically. As a consequence of this process the air increases in temperature and it is subsequently cooled in the second heat exchanger, HE2. The air is further dried in the second desiccant bed, DB2, before being finally cooled in the third heat exchanger, HE3.

The desiccant is regenerated by designing the heat exchangers HE1 and HE3 as effective solar collectors. Hence during the day ambient air leaving the fan is heated in the heat exchangers, thus reducing its relative humidity so that the desiccant beds are regenerated for the night cycle.

The underlying principles of operation of the stage-wise system can be understood from the psychrometric chart (Figure 2). Cool ambient air with a high relative humidity state 1 is compressed by the fan to state 2. It is this air that would normally be used for ventilating grain in natural aeration systems, but because of its high enthalpy it has limited cooling capacity. In the desiccant bed cooling system the air is cooled from state 2 to state 3 in the first heat exchanger, HE1. The air on entering the first desiccant bed, DB1, leaves at state 4, whence it is cooled by the atmosphere to state 5. Now this represents a reduction in enthalpy compared with natural aeration systems, but a further reduction is obtained by passing the air through the second desiccant bed, DB2, bringing it to state 6, before finally cooling it to state 7. It is this air that is used to cool the grain.

### **AN EXPERIMENTAL SINGLE-STAGE**

In order to assess the likely performance of the above system, a single-stage consisting of a fan, heat exchanger (HE1) and desiccant bed (DB1) was constructed, and comprehensively instrumented. The layout of the single stage and its associated instrumentation is shown in figure 3.

The heat exchanger-cum-solar absorber is 1.14m wide and 1.18m long, and the desiccant bed rests on a 100m wide perforated metal sheet in a container integral with the heat exchanger. Those parts of the device not directly exposed to solar radiation are thermally insulated with fibre-glass wool. On leaving the desiccant bed which may be up to 200mm high the air flows through a return leg before being expelled through the base of the stage. This design was chosen so that stages could be conveniently placed side by side in series.

The unit is comprehensively instrumented to allow the air flow rate and thermodynamic states to be determined throughout the system. The inlet air state is measured by wet- and dry-bulb thermocouples, and the dry-bulb temperature of the air is measured after compression by the fan just before it enters the solar absorber. Radiation-shielded thermocouples measure the temperature of the air leaving the absorber at four points, and as it enters the return leg immediately after it has passed through the desiccant bed. Wet- and dry-bulb thermocouples measure the state of the air being expelled by the unit. Electrically insulated thermocouples in close contact with the upper and lower plates of the absorber measure surface temperatures, and six thermocouples placed in the desiccant bed measure the desiccant temperature. A sampling probe allows desiccant to be removed from any depth of the desiccant bed at the front, middle and back of the bed, so its moisture content can be determined.

The air flow rate is measured by an orifice plate manufactured according to British Standards and the level of radiation is measured by a solar pyranometer calibrated against a CSIRO Division of Energy Technology secondary standard.

The experiments were carried out in the CSIRO Division of Energy Technology solar simulator (Proctor and Peck 1979), which consists of an array of fourteen 1 kW compact source mercury iodide discharge lamps that accurately mimic the solar spectrum.

## EXPERIMENTAL METHOD

When simulating daytime operation of the solar cooling stage the mercury iodide lamps were turned on together with the fan, and the air flow was adjusted to the required rate. At the beginning and end of each experimental run samples of silica gel were withdrawn from the bottom, middle and top of the desiccant bed, and the moisture contents of the gel were measured by an oven method. The thermocouples were scanned by a Hewlett-Packard 3421A thirty channel data logger, and the temperatures were stored on a mini 128 kbyte capacity cassette. Mean values of the intensity of solar radiation were determined by averaging the radiation measured at twenty five points on the absorber surface.

## RESULTS AND DISCUSSION

A series of five pairs of cooling and bed regeneration experiments was carried out with an air flow of 0.014 kg/s. This would be sufficient to cool up to 20 tonnes of grain. The cooling runs were carried out in an enclosed building during the day, hence the relative humidity of the ambient air is somewhat lower than would occur at night, and there was no radiation heat loss to the night sky. Conditions during a typical cooling run were:

Ambient dry bulb	15°C
Air temperature leaving fan	17°C
Absolute humidity of ambient air	0.0075 kg/kg
Air temperature leaving desiccant bed	31°C
Air temperature leaving single stage	21°C
Absolute humidity of air leaving single stage	0.0040 kg/kg

These results imply that as the air passes from the entrance of the desiccant bed to the end of the heat exchanger it is reduced in enthalpy from 36.5 kJ/kg to 31.5 kJ/kg. This would result in the dwell temperature of 11% moisture content wheat being reduced from 20°C to 17.5°C. The fan was operated for 6 hours during the cooling cycle and the average moisture content of the gel increased from 6.5% to 17%.

A heating run performed the day immediately after the cooling run was carried out under the following conditions.

Solar radiation intensity	840 W/m <sup>2</sup>
Ambient dry bulb	23°C
Air temperature leaving fan	26°C
Absolute humidity of ambient air	0.00085 kg/kg
Air temperature entering desiccant bed	52°C
Air temperature leaving desiccant bed	40°C

Absolute humidity of air leaving desiccant bed 0.0175 kg/kg

The mean moisture content of the desiccant bed decreased from 17.3% to a fairly uniform 4.4%. The efficiency of the solar collector was 32%, a figure that could clearly be improved by glazing.

Pressure measurements indicate that with an air flow rate of 0.014 kg/s the pressure drop across the solar collector/radiator is about 5 Pa, and that across the desiccant bed is around 55 Pa. Losses in the ducting and across the orifice plate were several hundred Pascals, but in commercial systems these would be readily engineered out.

### **EXPERIMENTS ON A TWO-STAGE SYSTEM**

In order to assess the overall performance of a two-stage system, two of the single stages described above were connected in series. As the two stages were too large to be irradiated in the solar simulator, experiments were performed under naturally occurring ambient conditions. Daytime cycles were of the order of four hours and night cycles had a duration of three hours.

Results of a typical night run in which the air flow rate is 0.014 kg/s are shown in Table 1. The enthalpy of air leaving the fan is reduced by the system from 29.7 kJ/kg to 13.4 kJ/kg. This arises principally from a reduction of humidity from 0.0068 kg/kg to 0.0013 kg/kg. Another contributing factor is a reduction in the air dry-bulb temperature by 2.2°C from 12.3°C such that it leaves the unit with a dry-bulb temperature lower than that of ambient due to radiation to the night sky.

**TABLE 1: Typical operating conditions during night cycle**

	<b>Ambient</b>	<b>After fan</b>	<b>Leaving 1st stage</b>	<b>Leaving 2nd stage</b>
Dry-bulb temp °C	10.5	12.3	13.8	10.1
Humidity kg/kg	0.0068	0.0068	0.0031	0.0013
Enthalpy kJ/kg	27.9	29.7	21.8	13.4

If ambient air were to be used for aeration, the dwell temperature of 11% moisture grain would be 16°C, whereas air leaving the solar cooler would be capable of cooling the grain to 6°C. The rate of heat reduction of the aeration air is 228 W, whilst the electrical power requirements is of the order 3.5 W. Assuming that the desiccant regeneration cycle has a duration twice that of the cooling cycle the coefficient of performance (COP) of the system based on the electrical power input is over 20. This is an order of magnitude greater than that of mechanical refrigeration sets. Based on total energy input, including solar energy, the COP is about 0.1.

The above results are most encouraging because they show that a substantial reduction in the enthalpy of ambient air can be obtained, with a small expenditure of electrical energy. However, further research is required in the following areas:

- i. It is important to extend the range of experimental variables in order to assess performance under conditions of high ambient dry-bulb temperatures and humidities which cause considerable storage problems. The effects of air flow rate on performance should also be investigated, as this determines the quantity of grain that can be cooled.
- ii. Systems studies, best carried out using computer simulations, are required to match grain cooling systems to the grain stores, and to determine the optimum operating schedule.
- iii. The effects of glazing the collectors for daytime operation should be examined. If air of a higher temperature is used to regenerate the desiccant bed, then a given mass flow of air can dry out a larger mass of desiccant. Hence, for a given drying duty it would be necessary to expend less energy on pumping the air through the desiccant bed during the day, improving further the coefficient of performance of the system.
- iv. The system would be improved if the desiccant bed were to work isothermally, as opposed to adiabatically, particularly during the cooling cycle. This could be achieved by placing heat transfer surfaces within the desiccant bed to facilitate the loss of heat of sorption to the atmosphere.

## **CONCLUSIONS**

Experiments on a single stage and two stages of a stage-wise solar regenerated desiccant bed grain cooler have shown that the enthalpy of ambient air may be reduced, thus rendering it more suitable for the aeration of grain. Under the conditions of the experiment the energy removed from the air is about 20 times the electrical energy required to drive the system.

## **ACKNOWLEDGEMENT**

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FIGURE 1: Components of a stage-wise solar re-generated desiccant bed grain cooling system

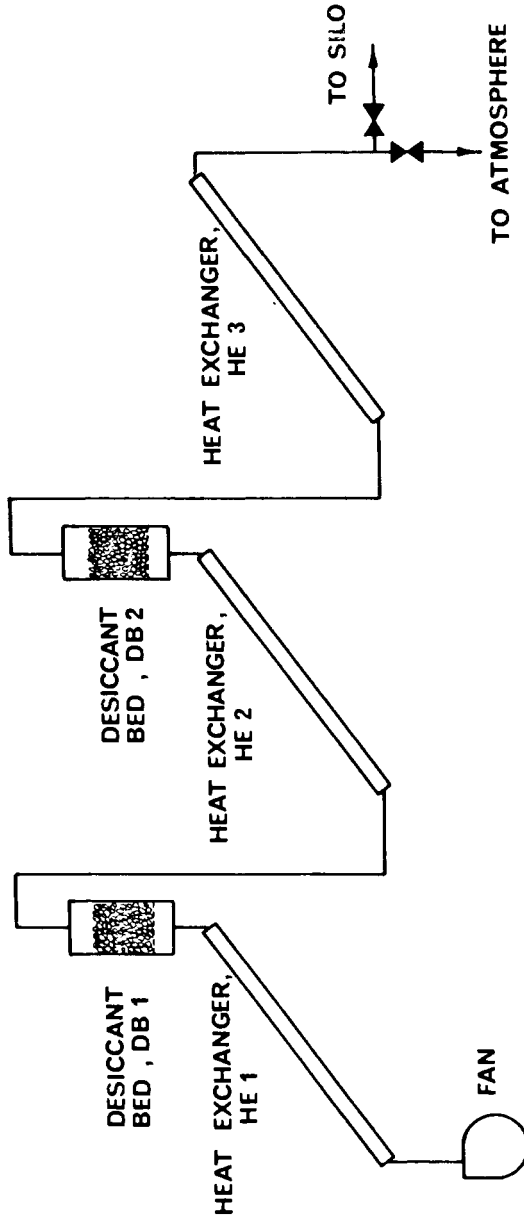
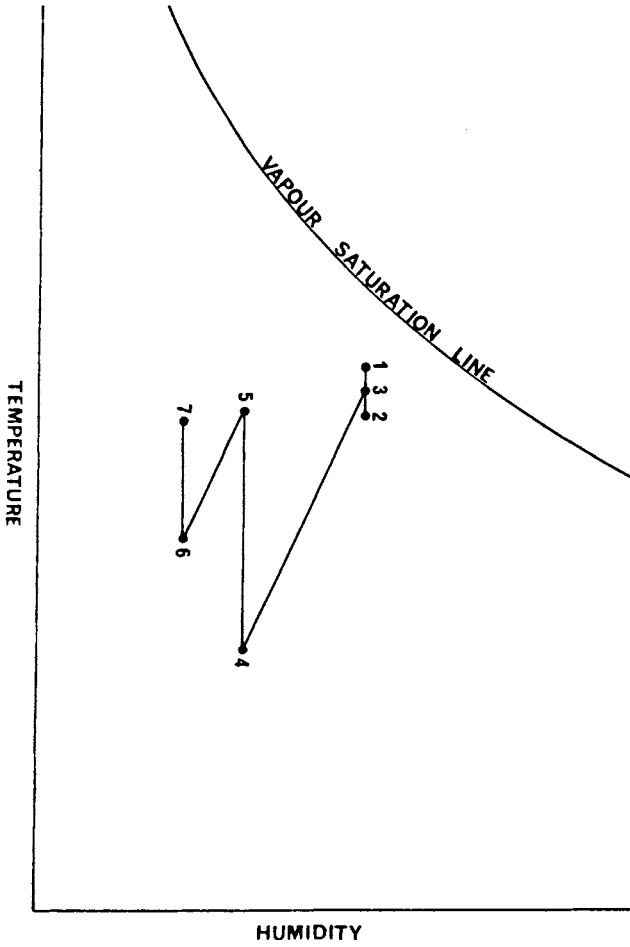


FIGURE 2: Air states represented on a psychrometric chart





## **DEVELOPMENT OF A THREE STAGE SOLAR DRYING SYSTEM FOR COFFEE**

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### **ABSTRACT**

The traditional practice of sun drying arabica coffee on tables is proving inadequate during the peak processing periods in some cooperative factories in Kenya. A three year programme to develop a solar drying system capable of maintaining a daily throughput of 3t of dried parchment coffee is described. The system consists of three separate stages: initial skin drying, intermediate sun drying on tables - mandatory for Kenyan coffee - and final drying. The skin drying and final drying stages take place in a purpose-designed building which incorporates a solar collector within the roof. Power is provided by a diesel-driven engine directly coupled to an axial-flow fan capable of maintaining an air flow of  $8 \text{ m}^3\text{s}^{-1}$ . Waste heat from the engine is used to heat the air thereby enabling drying to proceed in all but the worst weather and at night. The solar collector performed well within design specification with a collection efficiency of nearly 50%. In routine operating conditions system-dried coffee equalled that of control batches dried by the traditional method under ideal conditions.

### **INTRODUCTION**

Coffee has long been the major cash crop and export earner from the agricultural sector of Kenya. Current annual production is about 100,000 tonnes of clean coffee. Smallholder farmers are members of cooperative societies and their produce is processed in communal factories. The capacity of individual factories varies from 250 tonnes of (coffee) cherry or less each year to between 500 and 1000 tonnes per annum. One tonne of cherry yields approximately 200 kg of dried parchment which, in turn, yields about 160 kg of clean coffee.

In the factories the coffee is processed from freshly-picked cherry to dried parchment and then transported to warehouses for dehusking, sorting, grading and packaging before sale and export. The factory processing operations carried out include pulping/grading, fermentation, washing and drying.

Traditionally wet parchment is dried on wire-mesh tables. There are two distinct parts to this operation termed skin-drying and (for the purpose of this paper) bulk-drying, the drying of parchment from skin dry to fully dried. In the former operation wet parchment with a moisture content of 50-55% (all moisture contents quoted are on a wet-weight basis) is spread directly on to wire-mesh tables and sun dried with frequent stirring by hand until skin-dry, a moisture content of approximately 45%. It is then spread on hessian sacking on bulk-drying tables where it remains until dry at a moisture content of 10-11%. Skin drying can take from one hour to one day and bulk drying anything from 7-28 days depending on many factors including the degree of loading, weather, and amount of hand stirring. Both operations are labour intensive.

As well as removing the moisture from the parchment the table drying operation is essential to allow the exposure of the parchment to sunlight for the equivalent of four (sunny) days (McCloy, 1979) and hence correct flavour development. Exposure to light is especially important at moisture contents between 20% and 32% (Gibson et al. 1972).

An appreciable number of cooperative factories experience operational constraints due to table shortages during the peak processing periods (Whitaker and Roe 1985). In these periods up to 40% of the annual intake of cherry can occur in a single month which unfortunately invariably occurs within the rainy season. This period of maximum activity also coincides with other farming operations and the farmers find it difficult to fulfil their labour commitment to the factory. This general shortage of labour at the critical time counteracts a seemingly obvious solution - that of increasing the number of drying tables which in any case would be difficult due to shortage of land.

The estate sector faced similar problems, but with greater financial and technical resources have in many cases invested in large scale mechanical dryers over the last 10-20 years (Ghosh 1966, 1968; McCloy, 1979). Such dryers have been investigated for their suitability for cooperative factories (Kamau, 1980). High capital and operating costs and technical sophistication has meant that very few have been installed at cooperative factories.

In recent years efforts have been successfully directed towards increasing the smallholder production of coffee. In view of the potential escalation of the drying problem already being experienced by cooperative factories, the (Kenyan) Coffee Research Foundation (CRF) in collaboration with the Tropical Development and Research Institute undertook to re-examine the problem.

As a first step about 25 factories were visited and it was concluded that any improved drying system would have to satisfy the following requirements:

- i. A daily throughput of 3 tonnes of dried parchment.
- ii. Carry out both skin-drying and bulk-drying.
- iii. Accommodate the essential requirement of exposure to light during part of the drying process on sun drying tables.
- iv. Independent of external power supplies since 90% of cooperative factories are not connected to grid electricity.
- v. Minimum consumption of fossil fuels.
- vi. Total cost of the system excluding drying tables should not exceed 300,000 Ksh (US\$ 20,000) (at November 1982 prices).
- vii. Due to the general shortage of land the system should not increase the area required for drying.
- viii. Construction and subsequent operation should be as simple as possible. Construction should be carried out by local contractors using materials that are locally and easily available.

### **SYSTEM DESIGN FEATURES**

Taking into account the criteria stated above, a drying system was designed with three distinct stages:

- a. Skin drying, in which the moisture content of the wet parchment is reduced from 50-55% to 42-45%.

- b. Table drying, in which the skin dried parchment is spread on tables in the traditional manner and allowed to dry in the sun. The controlling factor for this stage of drying is the period of exposure to sunlight rather than the time to achieve a certain reduction in moisture content. However, after such a period of table drying, parchment will have dried to 15-20% moisture content.
- c. Final drying, in which parchment is dried in bins to 10-11% moisture content.

Skin and final drying are carried out within the same building as shown in Figure 1. A simple bare plate solar roof collector provides the principal source of heating during daylight hours. Additional heat is provided continuously by a moisture extraction unit (qv).

A diesel engine directly coupled to an axial-flow fan is used as an independent power source to move air through the final drying and skin drying bins. The engine and the fan unit, collectively termed a moisture extraction unit (MEU), is designed such that the fan draws air over and around the engine block thereby further heating the air and cooling the engine. The heated air is utilised twice for maximum utilisation of its drying capacity; it is first used for final drying and then for skin drying.

With the exception of the MEU, the system incorporates no mechanical parts thus minimising risks of breakdown. No instrumentation is required except for a thermometer.

### **SYSTEM BUILDING**

The flow of air through the system building is shown schematically in Figure 2. Air can either enter at one end of the collector and be drawn into the fan house or it can enter the fan house directly via the open fan house doors. In both cases it then passes over the MEU into the manifold duct from which it is directed into any or all of the five final drying bins, or by means of the by-pass duct, directly to the skin drying bin. In the latter the air, after passing up through the final drying bins under the bin covers to the skin drying bin, passes down through the bed of parchment before venting to atmosphere.

The quality of parchment may be impaired at temperatures above 35°. Hence the temperature of the air to the final drying bins is controlled by opening the fan house doors. This lowers the ambient air temperature in the fan house and reduced the flow of air through the collector. Air temperature is measured by a filled-system thermometer within the manifold duct.

The bare plate solar collector is an integral part of the roof of the building. It consists of black-painted corrugated iron sheeting under which is positioned a wood "ceiling" so forming a wide duct running the length of the building. The angle of the collector to the sun's rays and the orientation of the building are of obvious importance for optimising the collector performance. At CRF's Rukera farm near Ruiru, the location of the prototype system, the sun is to the south during the peak processing period of November-December. The collector was therefore designed running East-West and facing due South with a slope of 20°.

The flow of air through the collector is from end-to-end rather than from side-to-side because of the inherent difficulties in maintaining an even flow of air across a very wide duct with a fan centrally positioned along one side.

Buelow (1958, 1961, 1962) established that an increase in the flow of air through a collector of fixed dimensions leads to an increase in collection efficiency (ratio of energy gathered by the air flowing through the collector to the insolation incident upon the collector) but a decrease in temperature elevation of the air. Some loss in potential collection efficiency has to be tolerated therefore in order to obtain an air temperature that will ensure a satisfactory drying rate. Collection efficiency is dependent upon the heat transfer characteristics of the system (Whillier 1964). These in turn are a function of the air velocity through the collector. The velocity for a fixed volumetric flow rate is inversely proportional to the cross-sectional area hence the maximum collection efficiency would be obtained with a duct of minimum cross-sectional area. However, the greater the velocity the greater the pressure drop developed in the duct and the more powerful the fan required to move the air through the collector.

The dimensions of the collector are therefore a compromise between the conflicting demands of the collection efficiency, pressure drop and temperature elevation. For this application the collector was approximately 27m long and 7m wide with a spacing of 300mm between the roof and the ceiling.

There are five final drying bins within the system building positioned side-by-side alongside the manifold duct (Figure 1.) Each bin is 2.75m square and 1.20m deep and with a capacity of 4 t (dry) of parchment. The bins are rendered concrete block and have a perforated tray of wire mesh supported on wooden legs affixed to the concrete base of the plenum chamber. The flow of air to each bin through the inlet port is regulated by a wooden shutter raised by a chain from the catwalk above the manifold duct. The bins are covered by plywood sheeting supported at the side-walls of each bin but not at the end-walls. The bins are loaded from sacks through 0.9m square openings in the covers closed by wooden shutters. The parchment is unloaded from the bins into sacks via a discharge chute regulated by a wooden shutter.

The skin drying bin, likewise constructed, is positioned at one end of the line of final drying bins and separated from them by a by-pass duct. The bin is 6.40m long and 2.75m wide and can also hold 4 t of parchment. Air enters this bin either from the final dryings bins and/or the by-pass duct and flows down through the parchment bed. The air vents to atmosphere via ports in the end- and side-walls below the bin floor. Loading of the bin is likewise through openings in the covers and unloading through two discharge chutes as for the final drying bins.

The MEU is a commercially available machine (R A Lister Farm Equipment Ltd, Cirencester, UK) widely employed for the drying of tropical crops. The unit selected for the system uses a three-cylinder diesel engine with a shaft power output of 18 kW. The fan can provide an air flow of  $8 \text{ m}^3 \text{ s}^{-1}$  against a pressure of  $500 \text{ Nm}^{-2}$ . The MEU is mounted on a concrete plinth within the fan house (Figure 2). The fan casing is connected via a canvas coupling to the entrance of the manifold duct. Since it is imperative that the exhaust gases do not contaminate the parchment they are piped out of the fan house to atmosphere at roof level.

The roof of the manifold duct also acts as the catwalk for access to the drying bins. In addition, a concrete floor is laid on the far side to provide a clean and dry environment for unloading parchment and also a temporary storage area for full sacks waiting to be taken to the drying tables or store.

To prevent contamination of parchment the fuel drums for the MEU are positioned adjacent to the fan house wall with the fuel line running through the wall to the MEU.

### **SYSTEM COMMISSIONING**

The system was commissioned over a 38 day period in which 23 batches of parchment were dried. Wet parchment from the washing channels was pumped, for reasons of convenience, into the skin drying bin early in the morning and dried for 20-22 hours. It was then manually loaded into sacks and taken to the drying tables and remained there until the necessary time of exposure to sunlight had been achieved. It was then removed from the tables and taken, again in sacks, to one of the 5 final drying bins where it remained until dry. The final drying bins were used in sequence thus providing a 5 day operating cycle.

Control batches of approximately 100 kg were dried on tables in the traditional manner as a basis for quality comparison.

During commissioning air temperature and humidities at pertinent points within the system building were continuously monitored using multi-point chart recorders (Anville Instruments Ltd, Chertsey, UK). Manometers (Air Flow Developments Ltd, High Wycombe, UK) were used to measure the duct pressure and pressure drop across the beds of parchment. Insolation and wind velocity were logged using a solar distrometer and cup anemometer (Casella London Ltd, London, UK), respectively. When batches were dry, samples were taken for oven moisture determination. Every batch, both system dried and control dried, was assessed for quality employing standard techniques by the Coffee Board of Kenya (CBK) after conditioning in sacks for 4-5 weeks.

### **RESULTS AND DISCUSSIONS**

#### **Thermodynamic performance**

Mean daily insolation was  $21.9 \text{ MJ day}^{-1}$  (compared with the seasonal mean of  $20.3 \text{ MJ day}^{-1}$ ) and there was an average of 7.8 sunshine hours per day (compared with the norm of 6.4 hours). Such weather conditions resulted in high ambient air temperatures which necessitated the fan house doors to be open for long periods, on most days from 11.00 to 16.30. When the doors were open the flow of air through the collector was reduced by 50% to  $4.0 \text{ m}^3\text{s}^{-1}$ . Even though the collector outlet air temperature frequently rose as high as  $44^\circ\text{C}$ , after mixing with the cooler ambient air the temperature of the air flowing to the drying bins was within the required limits.

Table 1 summarises the collector performance over the commissioning period. Collection efficiencies were lower when the fan house doors were open compared with when all the air was drawn through the collector. This was to be expected since collection efficiency increases with increase in air flow even though temperature elevation may be higher.

The air heating performance of the collector is presented in Table 2 and meets design specifications. It is reasonable to conclude that the collector would be able to provide sufficient heat even during periods of more inclement weather likely to be experienced at other times. Opening of fan house doors proved effective as a means of regulating the air temperature.

From the data in Table 2 it can be calculated that on those days when the fan house doors were closed throughout, the collector provided 1800 MJ during the day time and the MEU 2400MJ over 24 hours, together supplying a total daily heat input of 4200 MJ. If an equivalent amount of energy was provided by electricity, a 50 kW heater would be required. Alternatively, if a direct-fired oil heater was used then approximately 120 litres per day of diesel oil would be consumed; more if for product quality reasons an indirect-fired heater were used.

Operating conditions for skin drying are presented in Table 3. The mean inlet air temperature for the 23 batches dried was 24.6°C and the outlet air temperature 17.7°C. The outlet air was for the most part saturated, ie at 100% relative humidity (RH), and never less than 90% RH. This indicates that the system was very effective in terms of utilising the capacity of the heated air to absorb moisture from the parchment.

Mean temperature of the inlet air to the final drying bins was 29.2°C and the outlet air temperature 24.8°C (Table 3). There was relatively little difference between the temperatures of the inlet and outlet air at night. This can be attributed to the inherently large heat capacity of the system. Particularly when a batch was almost dry the outlet air temperature was sometimes as high as 32° at 1800 hours and it can be taken that the parchment temperature was only a little lower. During the next few hours, even though drying continued, albeit slowly, the outlet air temperature was actually greater than the inlet air temperature, sometimes by as much as 5°C, due to the parchment and bin walls releasing heat absorbed during the day.

The MEU proved a very efficient and reliable machine. It was operated for nearly 800 hours with an average fuel consumption of 3.23 l.h<sup>-1</sup>. Since fuel consumption was somewhat greater, about 4.0 l.h<sup>-1</sup>, when the MEU was being "run-in", it would be expected to average 3.0 l.h<sup>-1</sup> in subsequent operations. For the most part of the commissioning period when all the bins were fully loaded the MEU delivered a constant air flow of 8.0 m<sup>3</sup>s<sup>-1</sup> against a pressure of 400-500 Nm<sup>-2</sup>.

The mean weight of the 23 batches processed was 2.94 tonnes although there was considerable variation in batch size as would be expected in any cooperative factory. There were three days when parchment was not available; on these days the parchment already within the skin drying bin was given an extra day of drying.

The mean reductions in moisture content achieved for each of the three drying stages and the times required to effect these changes (Table 4) are all within the system specifications. The mean rate of evaporation of moisture during skin drying was 49 kg h<sup>-1</sup> and that during final drying approximately 15 kg h<sup>-1</sup>. From these data the pick-up efficiency, the ratio of the moisture evaporated during the drying to that which the air is theoretically capable of evaporating under adiabatic conditions, was calculated. The efficiency of the system (61%) is satisfactory.

Because of the high moisture content moisture evaporation of the skin drying stage is rapid. This results in the air becoming saturated before it reaches the bottom of the bed. The parchment therefore tends to dry from the top down. To ensure even drying of the parchment it is necessary to thoroughly turn the bed twice during the day. This simple but very important procedure required two men for 20 minutes for each turning and proved very effective.

Because of the dry and sunny weather experienced during commissioning the necessary 30-35 hours of exposure of parchment to sunlight on the tables was invariably achieved within 5 days. Although there was considerable variation in the parchment loadings on the tables, 6.4-9.4 kg m<sup>-2</sup>, the rate of drying remained essentially constant.

The system has the in-built capacity to final dry each and any batch for about 110 hours (5 days and nights less unloading and loading times). The mean final drying time of 83 hours indicates that the system has sufficient in reserve to cope with less favourable weather. However, slightly better skin drying performance was possible if the air inlet ports to the final drying bins were closed at night and the air ducted straight to the skin drying bin. Final drying times for parchment were not significantly increased. It was therefore concluded that optimum system performance in this respect would be achieved if parchment is final dried continuously for 3 days and nights and then only during daylight hours of the remaining 2 days.

A similar procedure would be adopted during rainy periods. On rainy days final drying would be effective until the moisture content reached 12-13%. During these periods it is recommended that batches that have had at least 3 days (and nights) of final drying be isolated until the rain ceases and the air humidity drops. Skin drying can of course be pursued under all likely weather conditions.

Although a moisture gradient within the final drying bins of 1-2% from bottom to top was initially established it gradually decreased as drying proceeded. By the time moisture contents of 10-11% were reached the moisture gradient had virtually disappeared. There was no evidence either of any variation in moisture content across the beds thus indicating that air flow through the beds was evenly distributed; a fact endorsed by direct measurement of the air flow.

### **Product quality**

Regardless of how thermodynamically efficient the system or how fast parchment dries the most important feature for successful adoption of the system by cooperative factories will be the quality of the dried product. There was no significant difference in quality between the system dried coffee and the control samples. However, the system was commissioned over a sunny period which meant that the table drying conditions for the control batches were very favourable. It can be said therefore, that the system gave a product as good as that produced under ideal sun drying conditions. The quality of the dried parchment was not exceptionally good in absolute terms, Classes 4 and 5. (The lower the class number, the higher the quality.) However, data from CBK indicated that without exception this was not attributable to any effect of the drying process but to shortcomings in pre-drying operations such as poor pulping and fermentation operations.

### System economics

From data gathered from the commissioning and from data of traditional drying practices (Whitaker et al. 1985) it has been concluded (Whitaker and Roe 1985) that nearly 10% of all cooperative factories in Kenya, 55 in total, would benefit financially if the system was integrated with their present drying facilities. These factories are mainly those with a shortage of drying tables which would have to purchase land to build more tables. The number of factories benefitting could well be greater. For this evaluation the potential of the drying system to prevent quality losses under congested factory conditions was ignored because of the uncertainty surrounding the extent to which this occurs. Also, the convenience of the system was not taken into account. Furthermore, in many districts there is an upward trend in coffee production in the cooperative sector (Whitaker et al. 1985) and increasingly more factories will be experiencing drying problems due to shortages of tables and/or land.

### CONCLUSIONS

It has been demonstrated that the drying system is capable of efficiently drying 3 tonnes of parchment coffee and to a quality at least equivalent to that obtained under ideal sun drying conditions. The system building proved easy to construct by local artisans and labourers. The cost of the building and the MEU came within the budget specifications. The operation of the system proved simple and presented no problems to the factory staff. The economics of the operation are such that there are, at present, over 50 factories that could financially benefit from the system. There are also indications that this figure could increase if present production trends continue.

### ACKNOWLEDGEMENTS

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**TABLE 1: Solar Collector Performance**

Position of fan house doors	Insolation	Daily air temperature rise*, °C	Collection efficiency %
	MJ m <sup>-2</sup> day <sup>-1</sup>		
Open**	23.25	5.3	40.8
Shut	18.25	5.4	49.7

\* Mean over the 12 hour period 06.00-18.00

\*\* The fan house doors were only open for part of each day, approximately 11.00-16.30.

**TABLE 2: System Air Heating Performance**

Period*	Position of fan house doors	Air Temperature, °C			
		Ambient	After collector	Before MEU	After MEU
0800-1100	Shut	23.1	29.5	29.5	32.3
1100-1630	Open	28.9	39.8	34.4	37.1
1630-1800	Shut	26.4	29.5	29.5	32.8
1800-0600	Shut	18.7	18.7	18.7	23.1

\* The period times are approximate; there was considerable variation in the times the fan house doors were open depending upon the weather.

**TABLE 3: System Air Temperatures**

Operation	Period*	Air Temperature °C	
		Inlet	Outlet
Skin drying	0600-1800	27.1	18.7
	1800-0600	22.1	10.9
Final drying	0600-1800	34.3	25.3
	1800-0600	22.2	22.0

\* The period times, particularly for skin drying are approximate; there was variation depending on the availability of parchment.

**TABLE 4: System drying performance**

Operation	Drying time, h	Parchment moisture content % (wb)	
		At start	At finish
Skin Drying	21.2	53.2	42.6
Table Drying	33.5*	42.6	17.5
Final Drying	83.0	17.5	10.6

\* The time for table drying is the period parchment was actually uncovered on the tables and not the residence time of parchment upon the table.

**FIGURE 1: Parchment drying system building**

FIGURE 2: Air flow within system building

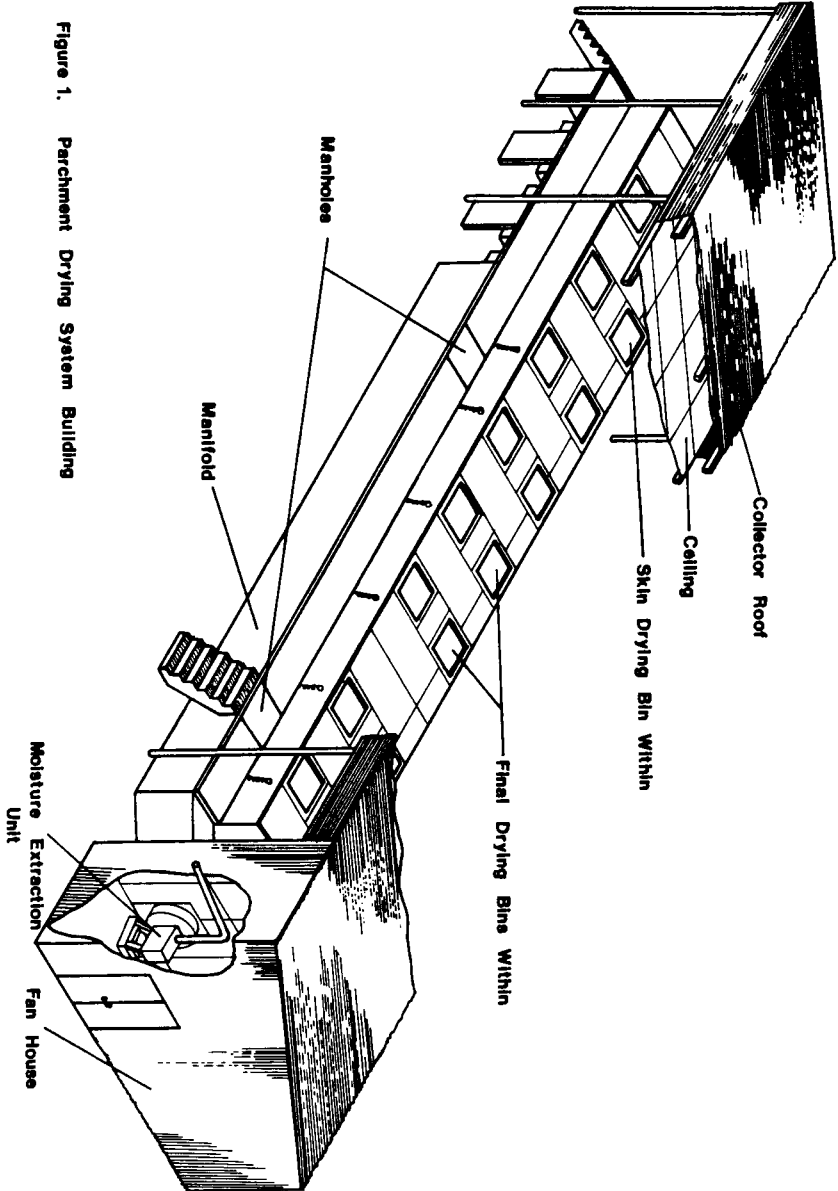


Figure 1. Parchment Drying System Building

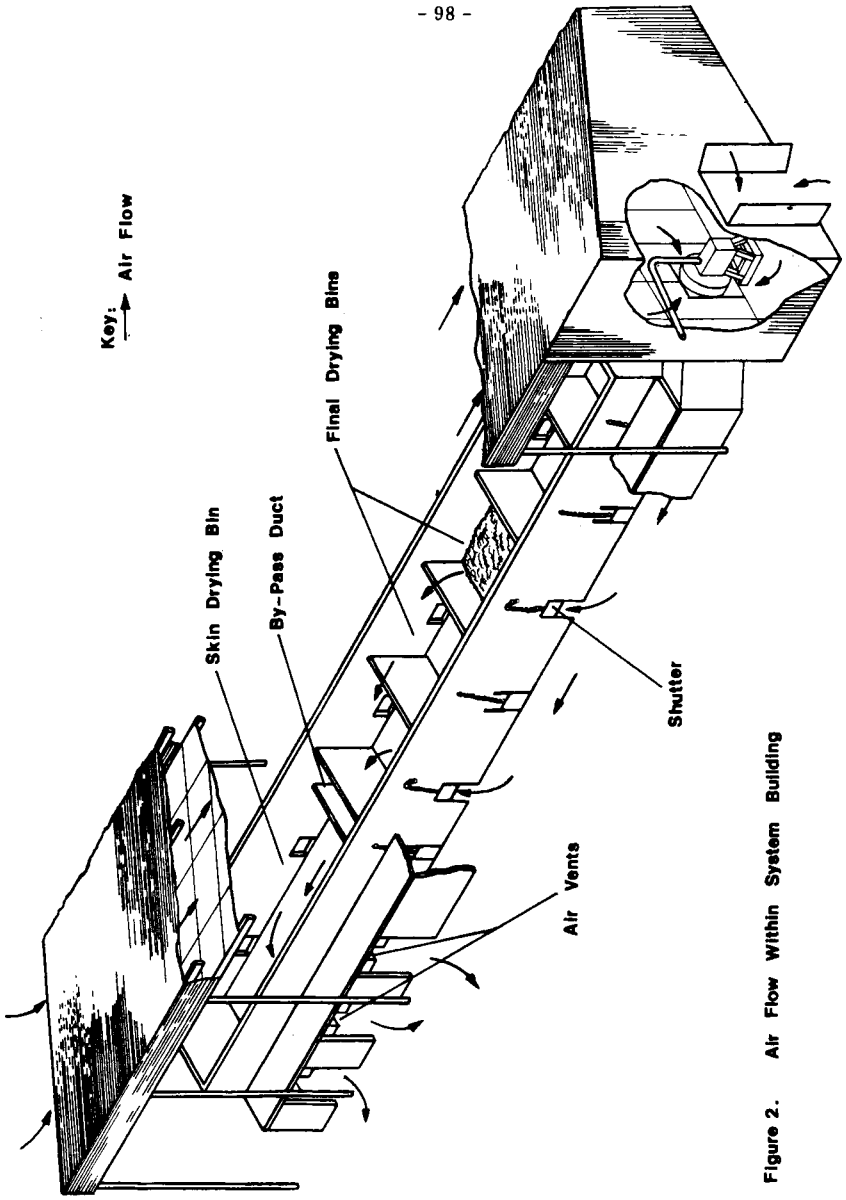


Figure 2. Air Flow Within System Building

## **DRYING OF ROBUSTA COFFEE IN UGANDA USING SOLAR HEATED AIR**

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### **ABSTRACT**

This paper discusses the use of low-temperature solar heated air for drying coffee berries. In comparison to open-sun drying, this method affords higher drying temperatures which considerably reduces the length of the drying period. Test results, using a tray type dryer are presented. A natural-convection chimney aided batch type solar dryer, is proposed for the typical rural setting.

### **INTRODUCTION**

Coffee has been the most important cash-crop since 1955, of late contributing well over 95% of the foreign exchange earnings of the country. Harvesting of the crop is spread throughout the year with harvest peaks in November-December and January-February for Robusta and Arabica respectively, the two main coffee varieties grown in the country.

The peak harvests generally coincide with months of frequent rainfall and thus of inclement weather conditions. This very often makes it difficult for the farmer to harvest, handle and safely dry the large volume of the readily perishable crop ("kiboko") from the normally high moisture level of up to 65-68% (wb), down to the safe-storage moisture level of 12% (wb). In addition to climatic problems, common to the Robusta growing areas in E Africa, labour during this period is scarce, being thinly divided between numerous other agricultural, farm and household operations.

This explains why a large portion of the "kiboko" delivered by individual farmers to the processing factories usually has a moisture content as high as 13 to 15% (wb) (Cowie 1963) and during years of bumper harvest, up to 16% moisture. Thus further drying is necessary at factories. Provision of a cheap, simple and reliable artificial drying technology at the grass-root level, would relieve the cooperative unions and the Coffee Marketing Board (CMB) from the task of re-drying the fairly high moisture crop received.

### **CURRENT PROCESSING AND DRYING PRACTICES**

#### **Wet processing**

Coffee is normally either wet- or dry-processed. Processing by the wet method starts by selectively harvesting the crop in the "red-ripe" stage (60-65% moisture wb) and preliminary grading of berries by sorting and "floating" in water. Good red-ripe healthy berries are subsequently pulped, fermented, washed and drained before drying. Compared to dry-processed crop, pulped and washed coffee is generally credited for its cleaner flavour, delicacy and fineness, and for freedom from undesirable elements. However, wet-processing requires capital equipment and clean water in quantities normally beyond the reach of a small scale farmer. In Uganda wet-processing has, therefore, until recently, been mainly confined to the Arabica crop at estates.

### Dry-processing

Robusta, representing 90% of the total coffee crop in the country, is an exclusively small holders' crop. Harvesting, particularly during the peak period, is still largely indiscriminate: involving mere stripping or "milking" of the bearing branches. The heterogeneous mixture of coffee berries, with a moisture range of 30-65% (wb) is then traditionally dry-processed in the cherry by the individual producers themselves, quite often without any sorting.

During the late 1960s, considerable attention and encouragement was given to wet-processing of the Robusta crop in the country (Anon 1964; Krug, 1968) in an effort to improve its marketing power and quality. These efforts were, however, abandoned due to the economic situation prevailing in the country during the 1970s.

More than half of the coffee bulk worldwide, both wet- and dry-processed, is still dried in the open sun (Haarer 1962). This process involves spreading the crop thinly on firm bare ground, on mats/sacks simply laid on the ground, or at best, on a cement surface or special raised wire-bottomed wooden trays.

Although the process appears cheap, it calls for large areas of drying space and is extremely labour intensive and slow. Drying, according to Cowie (1963), can take anything from 3 to 5 weeks to complete, depending on climatic conditions, the method of drying and the care taken. Often with poor handling, the crop is exposed to contamination which taints the flavour. It is also difficult to inhibit the growth of molds and microorganisms. The "mustiness" caused is the most serious taint of dry-processed Robusta coffee in Uganda and has in recent years been responsible for depreciation of the coffee export from the country.

### Mechanical dryers

When fossil and wood fuels were cheap and plentiful, mechanical dryers using these fuels gained acceptance in the coffee industry in Uganda, for direct or indirect heating of air for drying (Sivetz 1963; Ghosh 1966). At present day costs of these fuels, coupled with their scarcity and because of the impracticability of employing electrical dryers in rural areas where coffee is produced, it is essential to seek alternative energy sources for drying coffee (and other perishable agricultural crops).

This paper discusses the applicability of solar heated air to the drying of Robusta coffee in Uganda. Literature reviews (Allan 1965; Anon 1980, 1982) indicate that solar energy offers major potential as an improved and cheap method of crop drying, particularly in less developed countries of the tropics with abundant solar radiation - a cost-free source of energy.

## DESCRIPTION OF APPARATUS AND INSTRUMENTATION USED

### Experimental test rig

The experiments reported here were carried out during the 1983-84 coffee season, using an indirect tray solar dryer, designed and constructed at Kabanyolo University Farm, near Kampala. The test rig (Figure 1) consisted of a four-legged, box-like, wooden drying bin housing four independently movable wire-bottomed trays for the crop. The roof was of iron and a tall chimney aided air flow through the system. The drying trays were served by two flat-plate solar

collectors positioned symmetrically along the East-West trajectory, such that the sun rises on one side, passes almost vertically over both collectors, and sets on the other side. This arrangement is only suitable for locations very close to the equator.

Each of the collectors consisted of a blackened corrugated iron sheet (absorber) suspended between a corrugated sheet of clear fibre glass (heat trap) to the top, and a 50mm thick coffee-husk insulation sandwiched between two plywood sheets to the bottom

The solar dryer is simple both to manufacture and to operate, and the main construction materials can be obtained locally. The one major component not locally available is the axial flow fan. Consequently, this is the most expensive single unit of the system. Basic dryer parameters and technical data are given below:

#### **Basic dryer parameters**

- |    |                                 |   |
|----|---------------------------------|---|
| 1. | Solar dryer system              |   |
|    | - total length x width x height | 6.4 x 3.66 x 3.85m                                    |
| 2. | Solar collectors (two)          |   |
|    | - aperture area: 2(2 x 2.275)   | 9.1 m <sup>2</sup>                                    |
|    | - optimum tilt angle            | 15°   |
|    | - predicted mean power rating   | 7.5 kwh/day m <sup>2</sup>                            |
|    | - predicted mean efficiency     | 50%   |
| 3. | Drying trays (four)             |   |
|    | - length x width x depth        | 1.16 x 1.04 x 0.25m                                   |
|    | - max. volume: 4 x 0.3          | 1.2 m <sup>3</sup>                                    |
| 4. | Axial flow fan/electric motor   | recommended/available                                 |
|    | - volumetric flow rate          | 950-1000 m <sup>3</sup> /hr; (405) m <sup>3</sup> /hr |
|    | - static pressure               | 0.5-0.75" H <sub>2</sub> O                            |
|    | - power rating                  | 0.75-1.0 kw; (0.25) kw                                |

#### **Operation principle**

During operation, low temperature ambient air was forced, by means of an axial flow fan driven by a fractional horse-power electric motor, through a wooden T-junction air ducting unit. The air was then forced through the collectors where it was solar heated before going through the crop in the bin. Each of the collectors was optimally tilted for maximum collection of solar radiated energy particularly during the peak harvesting/drying period.

#### **Instrumentation**

To assess the performance of the solar dryer system throughout an experimental day, as the sun elevation and azimuth vary and weather conditions change, frequent and continuous observations of relevant meteorological states and temperatures of the working fluid and of the drying crop were made.

Table 1 gives ten-year mean values of the various meteorological elements for Kabanyolo University Farm. The dryer design was based on these data. Other important factors in the design were: crop type, chemical composition, and size of operation; harvest season, quantities handled, etc.

### EXPERIMENTAL PROCEDURE AND METHOD

Coffee used in this experiment was indiscriminately picked by farm workers. Prior to each test run, therefore, the heterogeneous mixture of berries was roughly sorted into two main moisture groups, ie 30-55% and 55-65% moisture (wb). The latter batch was used in these studies.

A 180-200 kg sample of berries was cleaned of all extraneous material and divided into four equal sub-lots for drying in the four wire-bottomed trays. A similar sample was uniformly spread, single layer, on a cemented drying floor (barbecue) to sun-dry as a "control".

Each day's test run normally lasted from 8.00 or 9.00 hours to 17.00 or 18.00 hours, depending on weather conditions. During test runs, various readings were taken either hourly or automatically recorded in graph or table form through instantaneous prints. The major parameters recorded, including details of locations and instrumentation employed, are summarised in Table 2. The fan was turned off whenever it started raining. At the end of a test day, trays were unsealed and the coffee in each tray thoroughly stirred prior to sampling for moisture level determination using a standard oven method described in Sivetz et al. (1963).

### RESULTS AND DISCUSSION

#### Working fluid temperature variations

Changes in temperatures of air within the dryer, the crop and ambient air are shown in Figure 2 and 3 for a typical sunny day. Figure 2 represents findings for a typical day during which a fan was employed. The ambient air temperature and at various locations in the dryer system, were very similar. That of the crop bulk in the bin, on the other hand, was slightly higher than the rest indicating that the batch, after the previous day's run, does not totally cool down to the ambient air conditions at night.

As the solar radiation gradually intensifies during the day air temperatures in all parts of the system rise, reaching their peak at approximately 13.00 hours. Thereafter, the temperatures dropped almost symmetrically. The maximum difference in temperature between the ambient and the air inside the collector, ranged from 15° to 20°C, while that between the ambient air and the crop ranged from 8° to 12°C. The latter greatly depended on the drying stage: being lowest when the crop was wettest (effects of self evaporative cooling by the crop), and vice versa.

Whenever the fan was not employed (due to power failure, for instance), air temperatures inside the collector increased to nearly 80°C for a typical ambient air temperature of 25°C. At the same time, the crop temperature rose only slightly above the ambient. This suggests that without the fan very little of the solar heated air passes through the crop. The drying rate, consequently, was reduced more than two-fold, as compared to not using the fan.

### **Collector performance**

Table 3 summarises the performance of the collector during a typical sunny day. In determining the efficiency of the collector, hourly ambient air temperature and mean hourly temperature rises inside the collector were used. With hourly solar radiation values known, the total theoretical energy collected by a collector of known aperture area, was evaluated hour by hour. The flow rate of the fan was taken to be approximately 95% of the fan flow rating: the difference accounting for air leakages through cracks and joints in the system. Collector efficiency was then determined, according to Mrema (1982), as the ratio of extracted energy to incident solar energy, per unit of collector.

For a typical sunny day, during the period of peak harvest, the collector was found to have an efficiency ranging from 10% at the start of the day, to 34% at peak performance; the mean being 25%. Further, the temperature rise and relative humidity were well within the required limits for a single glazed flat plate collector. On an overcast and cloudy or rainy day, the average collector efficiency was reduced to a mean of less than 10% and the changes in temperature and relative humidity were not as satisfactory as might be desired. However, the drying rate was still better than for open sun-drying. The efficiency-time relationships are shown in Figure 4.

### **Moisture removal pattern during drying**

Coffee well picked and dried in cherry, has an initial moisture level of 60-65%, as compared to the 50-54% moisture (wb) obtained in coffee pulped, fermented, washed and drained. When properly dried, the final moisture of the parchment, in both cases, should be 12% (wb). This reduction of moisture under conditions which will not harm the inherent qualities of the coffee is achieved by artificial or sun drying. Figure 5 shows the aviation of moisture of the robusta crop, dried in cherry.

During the initial drying stage, wet coffee readily loses moisture to the drying air. The process proceeds at a more or less uniform rate until the moisture level of 25-20% (wb) when the process gradually slows down towards the 12% moisture level. The gradual slowing down of water-rate loss occurs as the slimy, sticky mucilage that covers the seed, also starts drying; being much more impermeable to moisture the drier the coffee becomes.

For the test runs carried out during the 1983/84 coffee season, the period taken for the 180-200 kg batches to dry ranged from between nine days to sixteen days, each of approximately 8 hours of drying.

### **Coffee quality: its relationship to drying**

Coffee is a commodity which suffers from world over-production. Naturally, therefore, buyers can afford to be very selective and coffee offered for sale must be attractive with liquoring attributes positive enough to readily win consumer acceptability.

Drying of the crop is among the most important factors contributing to quality. Too slow a drying rate, with poor handling, causes mustiness and provides opportunities for a number of off-flavours. Drying the crop too fast and at temperatures higher than 60°C, results in case-hardening, bleaching of the berries to chalky-white, and browning of the roast, with consequent loss of

aroma. Failure to dry the crop to correct moisture levels, a process typical for traditionally dried robusta crop, breeds numerous handling and storage problems, resulting in very rapid deterioration of what would even have been regarded an excellent coffee product.

In Uganda an individual farmer handles the crop from the farm up to the point of hulling, either by a co-operative union or a licensed private processor, who then sells the crop to the Coffee Marketing Board (CMB) of Uganda. At the board, the coffee is tested for: moisture level, "defective" counts and size grades. Figure 6 gives the mean percentages of the robusta coffee received by the CMB (1979-1984) together with respective percentage-moisture levels. It is noted that less than 20% of the crop brought to the board actually satisfies the 12% moisture requirement by the board. More than 55% is received with moisture ranging between 13-16%, with mean moisture levels higher than 13%, prevailing during periods of peak harvests.

In a bid to combat this problem, the board imposes a monetary penalty on all coffee received at excess moisture, as follows: 7,000 Sh/ton; 10,000 Sh/ton; 17,000 Sh/ton and 22,000 Sh/ton respectively, for moisture levels of 12-13%; 13-14%; 14-15%; and 15-16% (wb). This practice has not been able to avert the problem particularly during peak harvest.

#### Grading coffee based on screen size

Table 5 shows the percentage weight of an average farm coffee produced from each screen size after the processing has been completed in the CMB. From the table, it is noted that Uganda's robusta crop is good, with the advantage that 25% is classed as "grade A" quality, and only 7% being graded as triage.

**TABLE 5: Grading through screening**

Grade		Screen size in 64th of an inch	Percentage production
1	A	17 and above	25
2	B	15 and 16	27
3	C	12, 13 and 14	21
Triage	Z	Below 12	7

#### Grading based "defective" counts

Based on defective counts, Appendix 1 shows the grading of coffee received by the CMB during the 1983-1984 coffee season; the defectives being dominated by those due to poor drying. It is noted that nearly all the coffee brought to the board falls within the "fairly average quality" (FAQ) classification. This stresses the importance of producers and owners of coffee co-operative unions, improving their methods of processing, particularly harvesting, handling, drying and storage of the crop.

#### Liquoring quality

Poor drying has negative effects on the liquoring quality of coffee. This is normally detected by smell and taste, and together with other coffee attributes, determine the price to be paid to the local marketing agents. After these have been paid their monetary dues, efforts are made by the board to improve the liquoring quality through "bulking", ie mixing various grades of coffee to obtain uniform appearance and cup taste to orient the crop for a particular market.

## **CONCLUSIONS**

As previously stated, weather conditions and drying space can make sun-drying of coffee wet- or dry-processed, impractical. To ensure high produce quality under these circumstances, farmers and estate owners will have to consider some form of artificial drying. The use of solar energy for coffee drying promises a feasible answer towards improvement in quality.

Uganda robusta is naturally good with advantage that approximately one quarter of the crop consists of bold beans retained by screen 17. The coffee when well dried and standard-roasted also affords a brilliant uniform roast, with rich heavy body - basic characteristics of good cup quality. It is therefore, up to the grower and processor to ensure that these natural quality attributes of Uganda robusta are amplified, and that by improved processing methods, particularly drying, the crop is afforded all the chances for better competition in the now discriminate and congested world coffee market.

## **ACKNOWLEDGEMENT**

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**TABLE 1: Ten year mean values for meteorological parameters  
at Kabanyolo University Farm**

<b>Meteorological parameter</b>	<b>Jan</b>	<b>Feb</b>	<b>Mar</b>	<b>Apr</b>	<b>May</b>	<b>Jun</b>	<b>Jul</b>	<b>Aug</b>	<b>Sep</b>	<b>Oct</b>	<b>Nov</b>	<b>Dec</b>	<b>Whole Year</b>
Solar Radiation (Langleys/day)	416	401	416	400	384	364	347	367	400	410	395	402	397
Sunshine hours (daily)	7.3	6.6	6.3	5.8	6.2	6.3	6.0	5.9	5.9	5.8	5.9	6.6	6.2
Maximum Temp (°C)	28	28	27	26	26	26	26	26	27	27	26	27	27
Minimum Temp (°C)	16	16	17	17	17	16	15	15	16	16	16	16	16
Daily Mean Temp (°C)	22	22	22	22	22	21	21	21	21	21	22	21	21
Relative Humidity (% at 0900)	88	89	90	92	91	91	92	92	90	89	90	89	90
Relative Humidity (% at 1500)	58	61	66	72	72	68	66	66	65	68	69	64	66
Precipitation (mm)	65	77	138	197	128	74	56	77	104	130	177	99	1322
Pot: Evapotr (mm) Penham	145	130	143	129	124	114	116	121	137	134	125	135	1553
Wind speed (m/s)	1.2	1.3	1.3	1.3	1.2	1.2	1.1	1.2	1.2	1.2	1.1	1.1	1.2

**TABLE 2: Summary of major parameters recorded with respective locations and instrumentation**

<u>Parameter and location</u>	<u>Instruments used</u>	<u>Remarks</u>
1. Temperature - of inlet ambient air (db & wb) - of ex-collector air (db & wb) - of centre of drying crop (db)	J-type copper/constantan thermocouple junction (wet-thermocouple provided with a thin wetted cotton wick)	Readings every minute printed in graphic form by a 6 point recording potentiometer
2. Insolation level in the plane of collector	Dome shaped solarometer with volt-time solar integrator, "Mark V"	Readings remote-record-printed as integrated hourly values ( $W/m^2$ hr)
3. Moisture content of drying crop	Gallen Kamp Oven, 250°C	Oven method recommended for coffee as in Sivetz (1963)
4. Static air pressure (laterally across collector)	A 15° inclined manometer and pitot tube	Manometer probes linked 15–20 cm from collector inlet and exit
5. Relative humidity - of ambient air - of air leaving bin	A polymer	Suspended under a well ventilated shade nearby, and at bin air exit
6. General weather conditions - wind speed and direction - rain and cloud cover - others of interest		Reading from the farm Meteorological station, located approx 400m away

**TABLE 3: Collector performance during a typical sunny day: November 1983**

Hour	Hourly Temp °C	Mean hourly Temp rise °C	Hourly R H (%)	Hourly Rad (KW/M <sup>2</sup> )	Integrated rad (Kwh)	Energy gain (kwh)	Collection efficiency %
8 - 9	19	1.5	85	0.225	2.05	0.21	10.25
9 - 10	22	7.5	78	0.530	4.82	1.03	21.37
10 - 11	25	14.5	66	0.813	7.40	2.00	27.06
11 - 12	26.5	21.0	57	0.972	8.85	2.89	32.66
12 - 13	28.5	22.0	53	0.978	8.90	3.03	34.04
13 - 14	27	13.0	55	0.686	6.24	1.79	28.69
14 - 15	27.5	14.0	56	0.716	6.52	1.93	29.60
15 - 16	24	7.0	61	0.477	4.34	0.96	22.12
16 - 17	22	3.0	69	0.238	2.17	0.41	18.89
<b>TOTAL</b>	-	-	-	<b>5.635</b>	<b>51.29</b>	<b>14.25</b>	-
<b>MEAN</b>	<b>24.6</b>	<b>11.5</b>	<b>64.4</b>	<b>0.626</b>	<b>5.70</b>	<b>1.58</b>	<b>24.95</b>

Remarks: Flow rate: 405 x 95% = 384.75 m<sup>3</sup>/hr = 492.48 Kg/hr = 0.1375 Kw/hr.

Clear day throughout with light NE - Wind; Maximum/Min ambient temperature respectively: 28.5°C/19 °C.

FIGURE 1: Tray solar drier

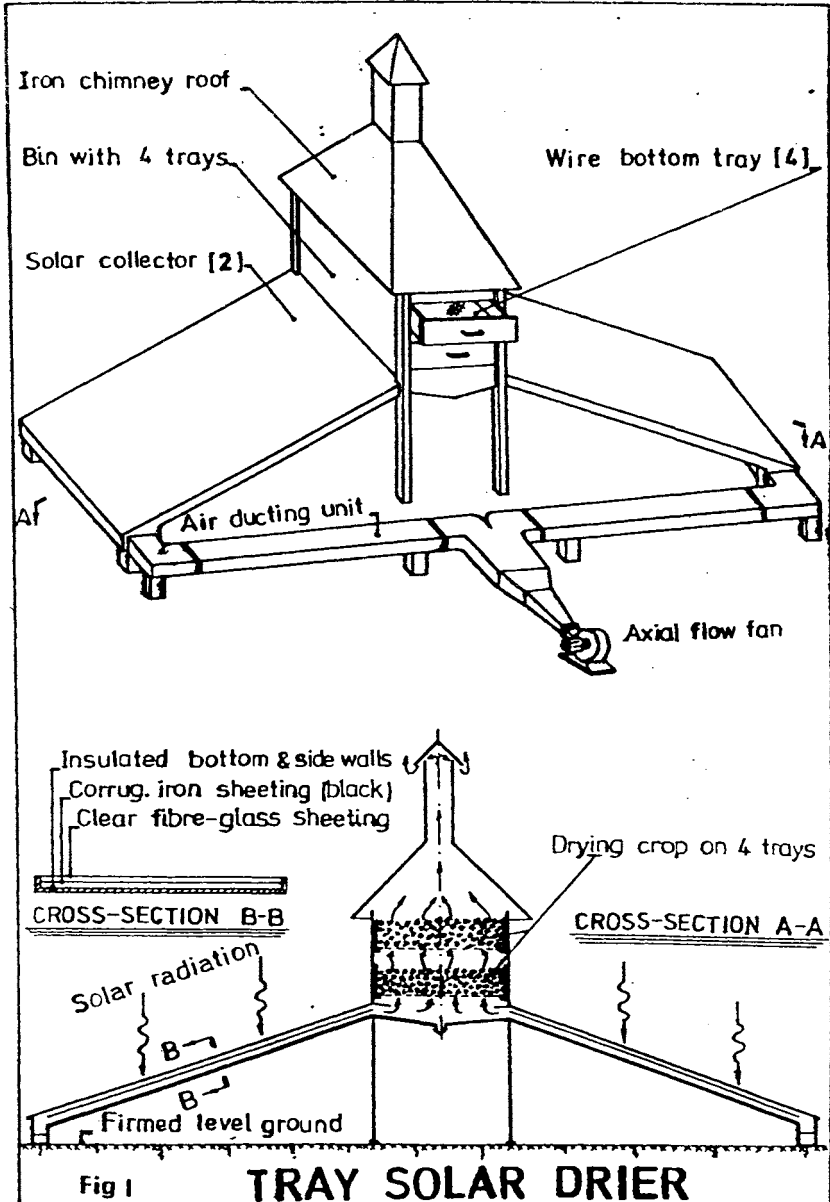


FIGURE 2: Variation of temperature with time of day (fan employed)

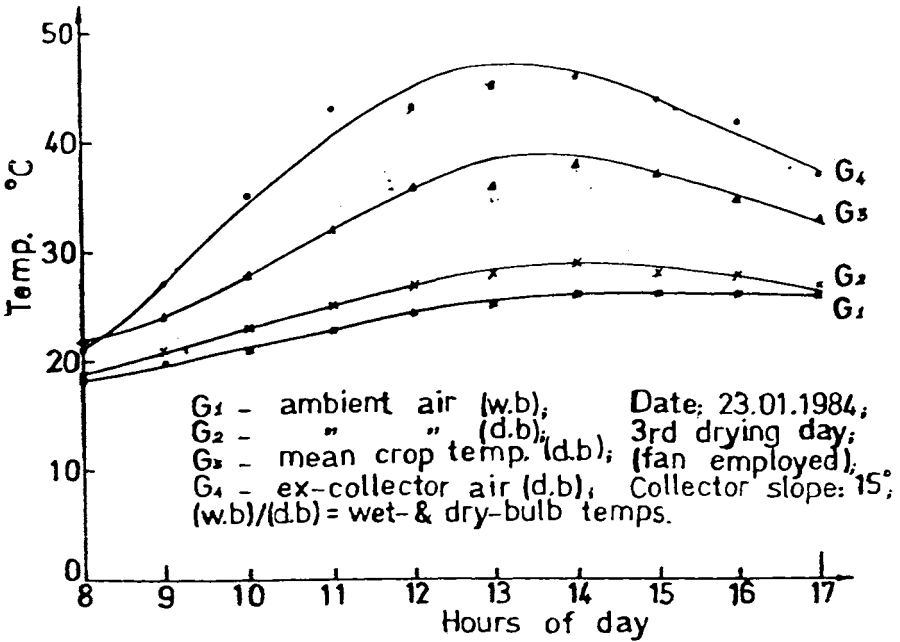


FIGURE 3: Variation of temperature with time of day (fan not employed)

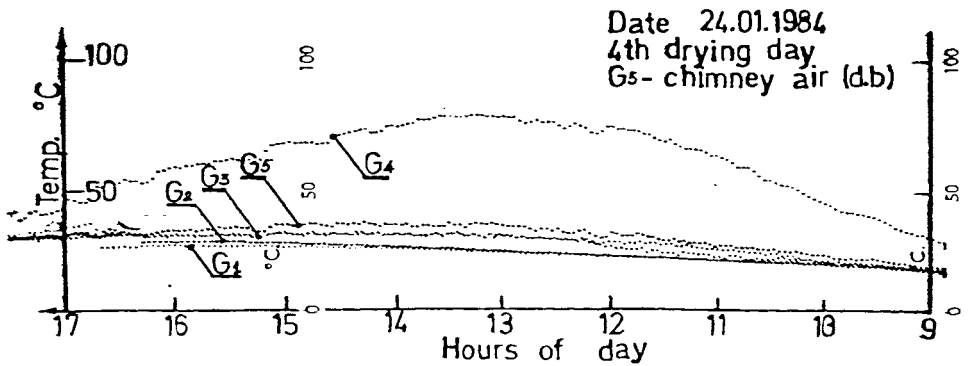


FIGURE 4: Efficiency-time relationship

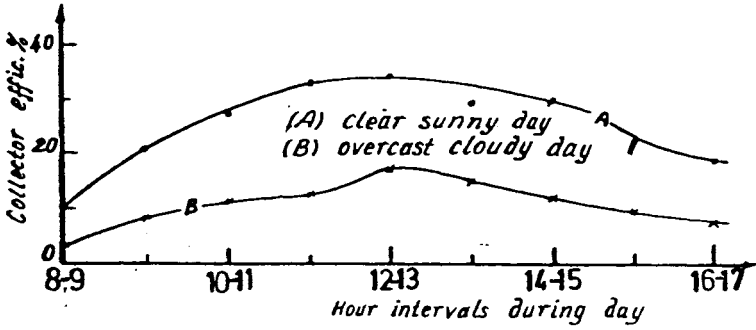
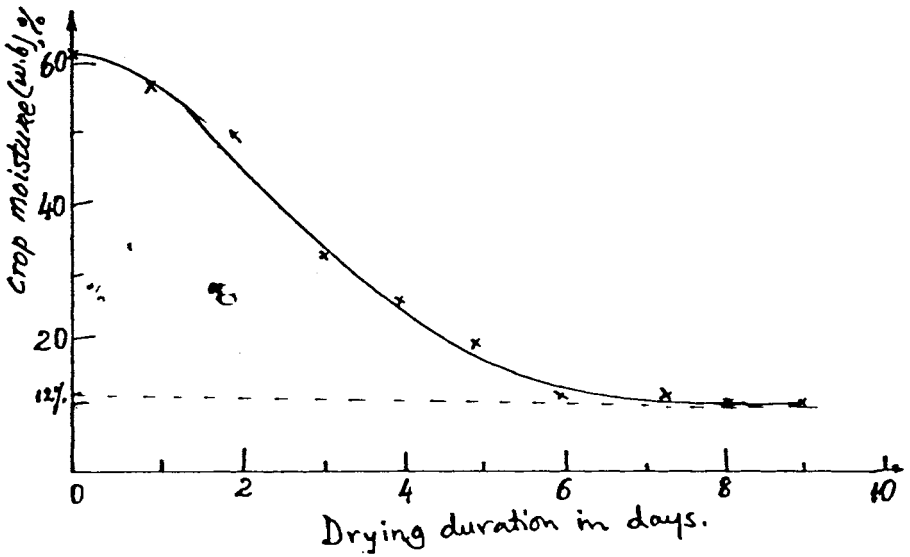


FIGURE 5: Moisture loss pattern



## **DESIGN CONSIDERATIONS AND PROTOTYPE TESTS ON A PYRETHRUM FLOW SOLAR ENERGY DRYER**

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### **ABSTRACT**

This paper describes a prototype solar energy dryer specifically designed to serve the needs of the small scale rural farmer growing pyrethrum. This is a "mixed type" solar energy dryer utilising a flat plate solar collector for air preheating and direct solar radiation on the crops. Prototype test results gave a system crop drying efficiency of 25.8% for the period October 1984 to February 1985. The quality of the dried crop was as good and sometimes better than that of crops dried by other methods.

### **INTRODUCTION**

Pyrethrum is a major source of foreign exchange currency for Kenya. It is harvested at a moisture content in excess of 75% (wb) and for safe storage and subsequent processing the moisture content must be as low as 15% (wb). The energy required for this type of moisture removal is substantial since Kenya's average year production of the wet crop is about 56,000 tons.

From the 1983/84 pyrethrum year Kenya, a non-oil producing nation, banned the use of the popular oil burning dryers by large scale pyrethrum growers due to the high cost of oil. Since the available electricity supply is already overstretched by industrial and domestic demands it cannot be diverted to crop drying purposes. There are only two alternatives: wood fired dryers or solar dryers. The former are currently well exploited, despite their fire hazards (Sebbowa 1985). But unless sufficient afforestation is undertaken these are bound to suffer the fate of the oil burning dryers. There are stringent regulations against the felling of trees and the price of wood fuel (presently as much as US\$36 per ton in some areas) may in the future make wood burning dryers uneconomical. Thus the long-term solution lies with solar energy dryers.

The average annual sunshine hours over most of the pyrethrum growing area of Kenya is 7.2 hours per day (Onyango *et al.* 1981) and average insolation is over 0.5 kW/m<sup>2</sup> (Sebbowa 1984). It is these favourable conditions which led to the design of a pyrethrum solar dryer whose design and performance are reported in this paper.

Of significant importance in the design procedure were the local constraints. Firstly, whether or not the design would be acceptable to the farmers. It was established that the medium and large scale producers (with yearly yields of over 4000 kg) tend to accept novel ideas readily and still use some form of mechanical dryer (Sebbowa 1985)

Secondly, it had to be established whether the prototype made economic sense. In financial terms the small scale farmer cannot benefit from it. Already all small scale farmers supply only dried flowers to their various cooperatives. However, for the large scale farmers a mechanical dryer is ideal to avoid congestion and/or delayed harvesting. When pyrethrum is harvested late its pyrethrins content (the active ingredient) is low as are the financial returns.

It is desirable that locally available materials are sufficient for the dryer construction to save foreign currency. And because of the type of end-users, the dryer while providing jobs in the fabrication had to be simple and easy to assemble and maintain.

### PYRETHRUM SOLAR DRYER DESIGN

The solar drop dryer is shown in Figure 1. It consists of a wooden dryer (2.25m x 2.3m and 2.3m height) with a 0.004m thick "ordinary window glass" roof. The cedar wood dryer walls are 0.02m thick and good thermal insulators. The dryer floor is made of similar wood boards to prevent downward heat loss. The pyrethrum flowers are dried on 10 trays stacked five high (tray spacing is 0.07m). Each tray is made of a wooden frame (1.05m x 1.9m and 0.115m deep) with galvanised wire mesh (0.006 m<sup>2</sup> mesh size). There is a 0.305 m<sup>2</sup> air inlet hole and the two outlet holes are 0.8m long by 0.101m wide. Otherwise the dryer is airtight.

To augment the direct heat supply to the crops from the dryer roof, a single cover flat plate solar collector (the air preheater) is used to pre-warm the inlet air to the dryer. The 0.68m by 3.0m collector consists of two ordinary galvanised corrugated iron roofing sheets (Gauge 30 BS) aligned with the troughs of one touching the crests of the other. This configuration, adapted from Gupta and Garg (1967) increases the air flow turbulence and hence heat transfer. The edges are sealed to make a leakproof airduct. The collector plate is housed in a galvanised iron housing from which it is insulated by glasswool (0.10m thick along the edges and 0.05m thick at the bottom). The collector cover plate is an ordinary window glass sheet (0.006m thick) secured onto the housing frame. The whole collector structure is inclined 6° to the horizontal in the north-south direction. Suitable galvanised iron ducting connects the matt black painted solar collector to a 1.5 kW electrically driven airblower and the dryer inlet (Figure 1).

### EXPERIMENTS

The results to be presented cover two areas. First, the performance of the solar collector as gauged by the temperature rise of the air flowing through it. Second, the performance of the dryer (provided with warm air from the air preheater) gauged by the time it takes to dry a given batch of pyrethrum and the dryer efficiency (TDRI 1984) for the available insolation. All results were obtained under forced convection of air. Although the recommended flow rate is 0.1 kg/s, a forced convection of 0.01 kg/s per unit area of dryer bed was used since in the long-term it is desired to use a low power airblower, if not completely natural convection (Githinji 1974).

#### Performance of the solar air preheater

Ideally the Whillier-Hottel-Bliss efficiency equation such as quoted by McVeigh (1978) should be used to calculate the solar collector efficiency. However, for quick practical purposes a somewhat simpler relation may accurately indicate the efficiency. The relation adopted in this work is

$$\eta_c = \frac{C_p \cdot m \cdot \theta}{A_c \cdot G}$$

where  $n_c$  = collector efficiency;  $C_p$  = mean specific heat of air flow through collector;  $\theta$  = temperature rise of the flowing air;  $m$  = mass flow rate of air;  $A_c$  = collector surface area; and  $G$  = insolation on collector surface. The specific heat,  $C_p$ , is not linear with temperature but in the temperature range of interest (15°C to 75°C) the variation is no more than 4.4 J/kg/K or 0.4%.

The rise in temperature of the flowing air,  $\theta$ , was measured with mercury in glass thermometers every 3 hours. The mass flow rate was constant at 0.0506kg/s. The insolation was measured in Langley's per day by a "Global Dome Solarimeter" at the national weather centre in Nairobi (5km from the prototype). The collector efficiency is shown in Figure 2.

### Drying performance of the system

Preliminary experiments indicated that a pyrethrum flower loading of about 120 kg of wet flowers led to more effective drying when rainy spells are likely to occur. Thus with an air flow rate of 0.0506kg/s this was the loading usually adopted. Higher loading levels resulted in slow drying and often flower rotting in the middle trays. 115 kg of fresh wet flowers was evenly spread on the ten trays, leaving aside about 5kg to be naturally sun dried on an identical tray as a control sample for dried product quality.

To determine the progress of drying a 10g sample was withdrawn from a representative number of trays (Tray Nos 1, 3, 8 and 10) every 3 hours and dried under a UV electric bulb on a moisture determination balance. Drying times ranged from 4-5 days.

The dryer performance was estimated by the drying efficiency  $\eta_D$ . In this case the efficiency  $\eta_D$  given by TDRI (1984) was slightly modified to account for the roof direct heating;

$$\eta_D = \frac{W.L.}{G(A_c + A_D)}$$

where  $W$  = weight of moisture evaporated (kg) during sampling interval,  $L$  = latent heat of evaporation of water (kJ/kg) at mean temperature of dryer,  $G$  = insolation (kJ/m<sup>2</sup>). During sampling interval,  $A_c$  = solar collector area (m<sup>2</sup>),  $A_D$  = dryer roof area.

The mean temperature of the dryer was based on the average between inlet to and outlet from dryer temperatures. A more precise method would require a record of the actual temperatures within the drying flowers. Nonetheless the values given in Table 1 are indicative of the drying efficiencies of the prototype solar dryer.

On completion of the drying of each batch a representative sample was analysed for pyrethrins content (or quality) by ultraviolet spectrogrammetry. A sample of the "open air" sun-dried flowers was treated similarly. Table 2 compares these samples with the known pyrethrins content of flowers for the same geographical location.

### DISCUSSION

The daily temperature rise indicated as expected that between the hours of 10 am and 4 pm the maximum temperature rise of the working air occurred. The

overall rise was related to variation in climatic conditions particularly cloud cover. Rain apparently has less effect than cloud cover.

The Whillier-Hottel-Bliss estimates of collector efficiency shown that efficiency is highest when the insolation is lowest. But without an accurate record of temperature across the collector plate and accurate monitoring of wind to measure the various losses, the efficiencies indicated are very approximate (McVeigh 1978).

Results for the drying capability of the system confirm previous findings (Sebbowa 1984). The drying time (4 to 5 days) is similar to that reported when pyrethrum flowers are sun dried (PBK 1985). But the average drying time (50.4 hours) is somewhat longer than the 35 hours previously reported. The 44% rise is probably due to the prolonged cloud cover especially for the batch dried in the period 1.11.84/9.11.84. Further, some rewetting occurred due to rain leakage through the dryer roof for this particular batch. When this batch is excluded the average drying time is 44 hours.

Periods with the least cloud cover generally yield the shorter drying periods. Initial moisture content also affects drying time. For example, one batch with a cloud cover of 55% but a low initial moisture content 76% (wb) had a similar drying time as a second which although having less cloud cover during drying (31%) had a higher initial moisture content 82% (wb). Thus while rain during the actual drying may be less significant than cloud cover it is important at the harvesting time since this is what determines the initial moisture content.

The drying system efficiency average 25.83%, is good when prevailing weather conditions are considered. Note again the effect of cloud cover for the 1.11.84/9.11.84 batch. It must be remembered that these efficiencies are based on available insolation on the topside of the glass cover plate for the solar collector plate and the dryer roof. No account is taken of the glass reflectancy or the glass material absorption. These would reduce the available solar energy thereby raise, albeit marginally, the dryer system efficiency.

The dried flower quality is comparable with the average for the Githunguri/Limuru areas. The seemingly lower values in Table 2(b) are due to overburning when wood fired dryers are used. That is except for the Kisii area where the low value corresponds to a poor harvesting technique.

## **CONCLUSION**

This work demonstrates that a fairly simple solar dryer designed with the aspirations of the pyrethrum growers of Kenya in mind is quite feasible. The drying times of 4 to 5 days during cloudy and sometimes rainy periods make the system relatively attractive. These times should be further improved with an blacker solar collector surface. Experiments in this direction are already underway and may be reported in the near future. However, to compensate for the somewhat longish drying times during heavy cloud cover and rainy periods a hybrid system incorporating solar energy and a wood fired system might prove best for commercial farmers. However, present wood fired dryers are very susceptible to fire. A recent survey (Sebbowa 1985) showed that most of the wood fired dryers have caught fire at one time or another. Perhaps in the end a solar energy system such as the one described in this paper is the only long term solution for pyrethrum drying.

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**TABLE 1: Dry efficiencies for the prototype dryer**

Batch	Available insolation	Energy for evaporation	Dryer efficiency
	(mJ)	(mJ)	( $n_d$ %)
14.2.85/16.2.85	644.35	201.35	31.25
23.1.85/28.1.85	924.83	212.72	23.0
10.12.84/15.12.84	788.88	225.91	28.6
27.11.84/2.12.84	901.53	240.91	26.7
1.11.84/9.11.84	1118.38	219.30	19.6

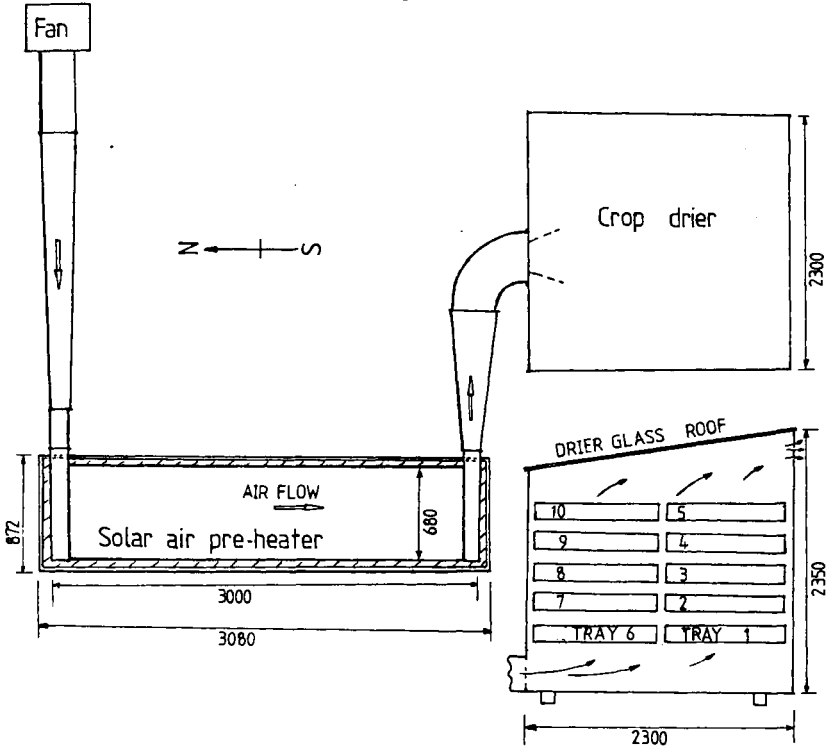
**TABLE 2(a): Quality (pyrethrins content of flowers dried in prototype)**

Batch	Pyrethrins content %	
	Dryer	Control sample (Sun dried)
14.2.85/16.2.85	-	-
23.1.85/28.1.85	-	-
10.12.84/15.12.84	1.670	1.680
27.11.84/2.12.84	1.620	1.680
1.11.84/9.11.84	1.626	1.640

**TABLE 2(b): Average national quality (pyrethrins content) of flowers (some flowers firewood dryer dried, others sun dried)**

Locational area	Pyrethrins content %		
Githungri	(1°S 37°E)	1.65	(Supplied first three samples)
Limuru	(1°S 37°E)	1.50	(Supplied last two samples)
Nakuru	(0°N 36°E)	1.49	
Meru	(0°N 37°E)	1.90	
Kisii	(0°N 35°E)	1.20	(99% sun drying)
Molo	(0°N 36°E)	1.50	

FIGURE 1: Solar crop drier system



Solar air heater

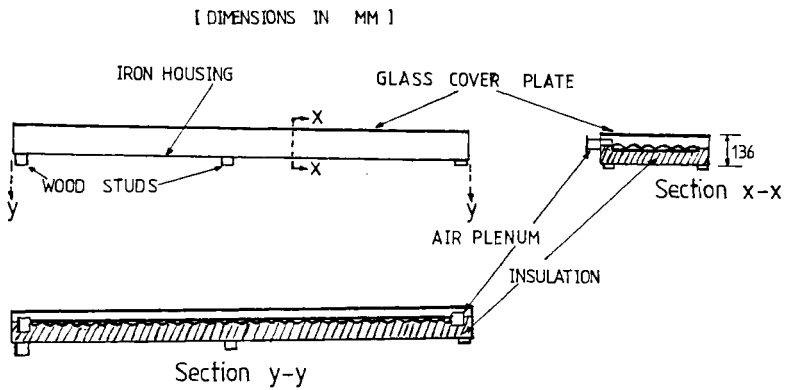
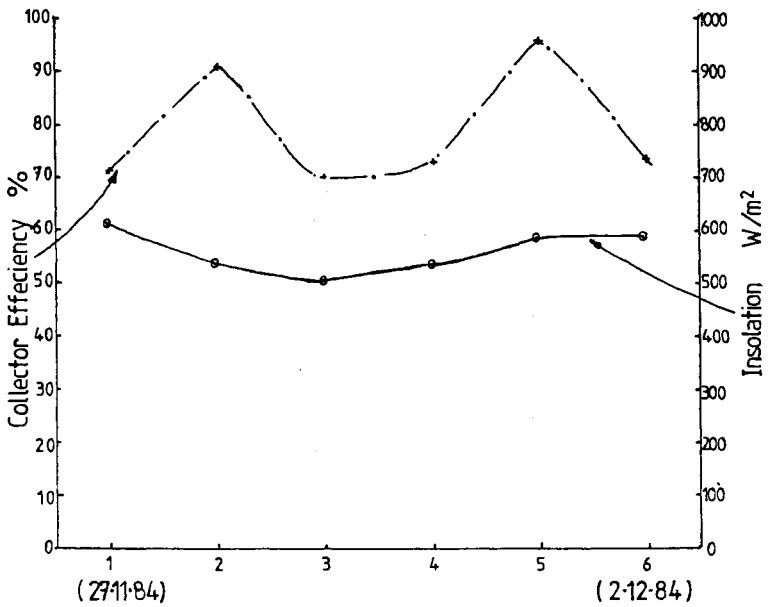
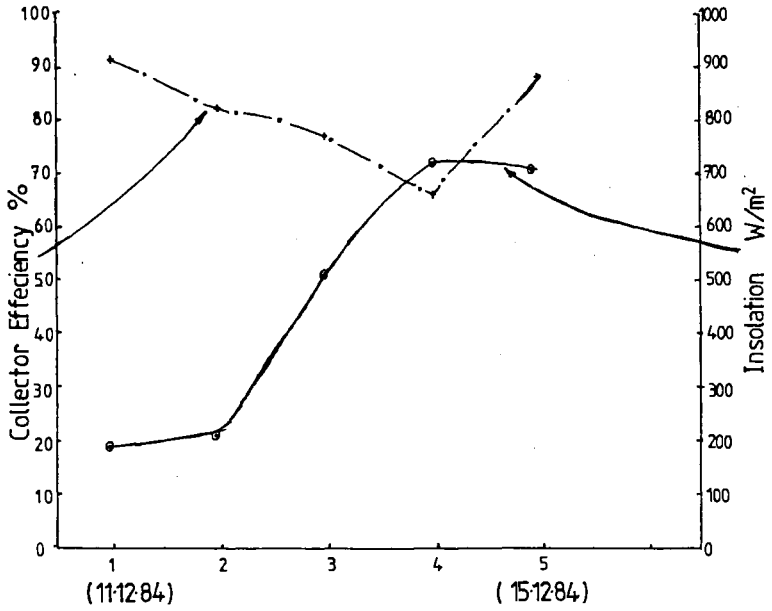


FIGURE 2: Insolation and collector efficiency vs day



## **DEVELOPMENT OF A SOLAR DRYING TECHNOLOGY FOR THE DEHYDRATION OF VEGETABLES IN ZAMBIA**

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### **ABSTRACT**

A survey of traditional methods of drying vegetables indicated a need for improved drying facilities in rural areas. Laboratory tests identified the optimum pretreatments for cowpea, pumpkin and delege leaves, when using an indirect solar dryer. A model for improving the procedures for drying these vegetables, with recommendations for organising the drying facilities is presented.

### **INTRODUCTION**

The practice of direct solar drying of vegetables and the utilisation of dried vegetable products is well established in Zambia.

A preliminary survey was carried out to identify traditional drying technologies, the specific vegetable crops to which these technologies are applied and the uses of dried products. The pilot plant survey was confined to limited locations within the Southern, Eastern, Central and Lusaka provinces.

The results of the survey indicated that:

1. Drying was carried out towards the end of the rainy season and to overcome the anticipated seasonal shortages in the dry season.
2. Dried products were stored over 2-3 months for use in the late dry season.
3. All products were subjected to pretreatments such as blanching.
4. The most common vegetables for solar drying (SD) are pumpkin, cowpea and delege leaves.
5. Occasionally collective drying was carried out using common drying sites (flat stone surfaces) but generally drying capacity was limited by lack of an adequate and organised technology.

The survey suggested two areas that required further investigation with a view to improving the processes for preserving vegetables. These were optimisation of pretreatment procedures to ensure the minimum loss of nutrient value, and, second, an improved system for drying material based on a solar heat collector. Since pumpkin, cowpea and delege leaves were the most common crops preserved in this way these were selected for further investigation.

### **OPTIMISING PRETREATMENT PROCEDURES**

The traditional pretreatments, including hot water or steam blanching, mincing and crushing, and pressing to remove excess moisture, were evaluated. The effect of such pretreatments on the quality of the dried product was measured under laboratory conditions.

Blanching time was determined and optimised using the residual polyphenol oxidase and peroxidase tests. The carotene and ascorbic acid content of the dried products were evaluated as parameters of nutritional quality. The effects of two levels (high and low) of:

1. Water: Vegetable (W/V) ratio
2. Blanching time
3. Drying temperature

on carotene and ascorbic acid content of the dried product were investigated using a full factorial experimental design.

The results are shown in Tables 1 and 2. Analysis of variance showed that for pumpkin leaves, the effect of W/V, blanching time and drying temperature (at the two levels tested) had no significant effect on the ascorbic acid and carotene levels in the dried product. In cowpea the effects of blanching time and drying temperature were significant ( $p > 0.05$ ) in the case of ascorbic acid.

Since the effect of W/V on ascorbic acid and carotene retention was not significant, water blanching could be recommended, though water blanching is known to result in heavier losses of water soluble nutrients such as ascorbic acid, than steam blanching.

Based on enzyme inactivation studies, six minutes was selected as the optimum blanching time for both steam and water blanching of the leaf vegetables under study. The effect of drying temperature, particularly on ascorbic acid content was dependent on the level of blanching time, a low blanching time in combination with low drying temperature being the most ideal.

#### **DEVELOPMENT OF A SOLAR DRYER**

Preliminary testing of a tent-type solar dryer resulted in heavy losses of ascorbic acid and poor colour retention. An indirect solar dryer was constructed, consisting of a separate solar collector attached to a drying chamber. The collector was constructed of corrugated iron sheets painted black and covered with a single layer clear polythene sheet. The collector chamber was insulated with dried grass. The drying chamber was constructed from wooden planks and included four shelves, each capable of taking three trays, 96cm x 51cm x 5cm. The drying chamber was provided with a chimney for improved convective air flow.

Drying tests were conducted using cowpea, pumpkin and delele leaves. Delele leaves are traditionally not blanched due to their mucilaginous nature and high water uptake in blanching. In these tests unbleached and steam blanched samples of delele leaves and both water and steam bleached samples of cowpea and pumpkin were used.

Table 3 summarises the drying time and temperature drying parameters for the three types of leaf material with a maximum tray loading of 1.0 to 1.5 kg of raw vegetable. A maximum drying temperature of 40-42°C was obtained in the drying chamber on clear sunny days resulting in an 18-20°C temperature rise above ambient temperature and a drying time of 28-50 hr.

Under cloudy conditions, maximum chamber temperatures were in the range of 24-34°C (10-14°C above ambient temperature) resulting in an extended drying time of 50-60 hrs.

Pretreatment also affected the drying time. Steam blanched and unblanched material dried faster than water blanched material under the same drying conditions.

The dried products had good colour retention and rehydration properties, with steam blanching resulting in better rehydration than water blanching (Table 4). The carotene content of the dried products was consistently high though ascorbic acid losses appeared to be higher than in traditionally dried products due possibly to a slower drying rate (Table 5).

Table 6 suggests that the recommended daily allowance of carotene (7500 IU of provitamin A or carotene) is provided in less than half of the quantity of solar dried material (pumpkin leaf) than that required of traditionally sun dried leaves.

### **CONCLUSION**

From the survey of traditional methods of drying vegetables, it is clear that there is a need for improvements in the drying facilities in the rural areas in order to increase the output and improve the quality of the dried product from both the nutritional and aesthetic points of view.

Though it was not possible to optimise the drying process through computation of mathematical models, some appropriate input variables have been defined for constructing a drying model suitable for use in rural communities.

### **The proposed model**

In designing the drying model two main inputs are considered: blanching and drying.

- a. **Blanching:** Both steam and water will be used but the selection of either option will depend on the conditions prevailing on a particular day. For example, steam is proposed for blanching on cold, cloudy days when there is little sunshine available. Only steam is proposed for blanching delele leaves which are not traditionally blanched owing to their mucilaginous nature. The use of steam will be favoured where there is scarcity of water. Water will be used on clear, sunny days for blanching vegetables other than delele leaves, and for economy the minimum necessary to completely immerse the vegetables will be used. A maximum of 6 minutes and a minimum of 5 minutes blanching time is proposed for all vegetables. Air cooling rather than water cooling is to be applied after the blanching, especially on a cloudy day.
- b. **Drying:** An indirect solar dryer is to be used and a temperature of 30-50°C is expected in the drying chamber depending on weather conditions on a particular day. A tray-load of 1.0-1.5kg of raw materials will be employed to effect satisfactory drying.

The model is expected to be a simple and low cost process for drying. To this effect as much as possible of the basic requirements will be procured from the locality. If possible the drying facilities will be established near to a stream or a river to facilitate ready access to a water supply. Containers for blanching will be made from epoxy painted drums or other cheap large cooking pots. Steam will be generated by boiling water in the drum. Fuel, eg wood, for boiling water will be obtained locally. The dryer itself will be constructed from materials available in the locality. The drying chamber to be brick or mud.

There exists a tradition of group or community drying on flat stone surfaces. This tradition will be exploited and built upon by encouraging vegetable drying on a cooperative basis. Presently only one such cooperative venture exists in the country - the Chikuni vegetable and fruit growers and processors cooperative in the Southern Province.

Some aspects of the proposed model have been tested in the laboratory and the results are quite encouraging. Higher drying temperatures have been obtained than in traditional sun drying. There is better nutrient retention and vegetables are dried under more hygienic conditions. The material being dried could also be left overnight in the dryer without risk from rain, contamination by birds, insects, dust and others.

TABLE 1: Total carotene in dried pumpkin leaves (mg/100g solids)

Treatment		Repeats			Treatment total	Total for 2 temp	Treatment mean
Blanching water (l)	Blanching time (min)	Drying temp (°C)	1	2			
30	4	50	55.3	63.8	77.7	196.8	65.60
		80	53.2	62.8	48.1	164.1	360.9
80	4	50	68.2	61.1	55.3	184.6	61.53
		80	60.4	55.5	54.9	170.8	355.5
80	8	50	62.4	63.0	69.0	194.4	64.80
		80	51.0	70.4	55.7	177.1	371.5
80	8	50	51.1	68.0	51.4	170.5	56.83
		80	59.3	60.8	61.0	181.1	351.6
			<b>460.9</b>	<b>505.4</b>	<b>473.1</b>	<b>1439.4</b>	

TABLE 2: Ascorbic acid in dried cowpea leaves (mg/100g solids)

Treatment		Repeats			Treatment total	Total for 2 temp	Treatment mean
Blanching water (l)	Blanching time (min)	Drying temp (°C)	1	2			
30	4	50	46.3	24.8	37.0	108.1	36.03
		80	23.1	16.4	18.2	57.7	165.8
80	4	50	13.6	19.1	20.9	53.6	17.86
		80	24.3	16.2	16.8	57.3	110.9
80	8	50	36.7	23.8	38.2	98.7	32.90
		80	23.2	22.9	19.2	65.3	164.0
80	8	50	14.8	18.2	14.1	47.1	15.70
		80	18.7	17.4	13.3	49.4	96.5
			<b>200.7</b>	<b>158.8</b>	<b>177.7</b>	<b>537.2</b>	

**TABLE 3: Summary of the drying experiment**

Vegetables	Treatment	Amount of material (kg)				Drying period (hrs)	Ambient temp °C (AV)	Drying temp °C (max)	Temp rise above ambient (°C)
		Tray load	In	Out					
Pumpkin	Water blanched:	1.0	3.0	0.383	51	20	34	14	
		1.3	1.3	-	50	24	42	18	
Cowpea	Water blanched:	0.453	0.453	0.084	27	20	34	14	
		1.0	2.0	0.179	60	22	32	10	
Delele	Unblanched:	0.595	0.595	0.070	29	22	32	10	
		0.507	0.507	0.15	27	24	42	18	
	Steam blanched	0.291	0.291	0.054	28	24	42	18	

**TABLE 4: Mean moisture, total carotene and ascorbic acid content: dehydration ratio and rehydration ratio of solar dried pumpkin, cowpea and delele leaves**

<b>Vegetable</b>	<b>Treatment</b>	<b>Moisture %</b>	<b>Dehydration ratio</b>	<b>Rehydration ratio</b>	<b>Total carotene mg/100g solids</b>	<b>Ascorbic acid mg/100g solids</b>
Pumpkin	Water blanched:	10.4	8:1	6:1	39.1 (69.1% Rtn)	14.8 (2.3% Rtn)
	Steam blanched:	6.7	5.4:1	7:1	41.7	21.4
Cowpea	Water blanched:	7.9	11.2:1	4:1	43.3 (83.1% Rtn)	16.3 (2.0% Rtn)
	Steam blanched:	6.8	8.5:1	6:1	59.5	246.8
Delele	Unblanched:	6.5	3.4:1	5:1	35.5 (91.3% Rtn)	151.6 (25.6% Rtn)
	Steam blanched:	7.0	5.4:1	6:1	41.8	199.2

**TABLE 5: Carotene and ascorbic acid content in traditionally dried pumpkin leaf and cowpea leaf from the Northern Province**

<b>Vegetable</b>	<b>Carotene mg/100g solids</b>	<b>Ascorbic acid mg/100g solids</b>
<b>Pumpkin</b>		
Unblanched:	16.2	47.6
Blanched:	18.5 (32.7% Rtn)	34.9 (5.5% Rtn)
<b>Cowpea</b>		
Unblanched:	35.6 (68.3% Rtn)	55.9 (7.0% Rtn)

**TABLE 6: Amount of fresh and dried\* vegetable necessary to provide the equivalent of 7500 i.u. of carotene**

<b>Vegetable</b>	<b>Fresh (gm)</b>	<b>Traditionally sun dried (gm)</b>	<b>Solar dried (gm)</b>
<b>Pumpkin</b>			
Unblanched:	52.9	30.2	-
Water blanched:		26.5	12.5
Steam blanched:		-	11.7
<b>Cowpea</b>			
Water blanched:	57.7	13.7	11.3
Steam blanched:		-	8.2
<b>Delele</b>			
Unblanched:	46.4	-	13.8
Steam blanched:		-	11.7

Assuming dried vegetables with 8% moisture content.

## **SOLAR DRYING OF SELECTED FOOD COMMODITIES IN ZIMBABWE**

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### **ABSTRACT**

A project to develop dryers for small scale drying and relying on natural convection has been launched. Baseline data regarding the solar climate of Zimbabwe has been collected. Radiation, temperature and relative humidity data show that there is a good potential for solar energy applications. A survey of products currently being dried as a means of preservation by the rural people in the various regions of the country revealed a wide range of commodities, such as leaf vegetables, fish, meat and edible caterpillars. The project will evaluate nutrient losses on traditionally dried fruit and vegetables with a view to improve nutrient retention and will also investigate ways of reducing harvest losses.

### **INTRODUCTION**

The climate of Zimbabwe is characterised by one rainy season extending from mid-November to mid-March with the rest of the year dry.

The cultivation of major crops and vegetables tends to be limited to the wet season. The availability of these food commodities tend to follow the seasonality determined by the rain cycle - being over-abundant during the rainy season and scarce or unavailable during the rest of the year. The availability of other food commodities (such as fish) also follows a seasonal pattern, albeit to a lesser degree and for different reasons.

Food preservation is essential to protect against spoilage due to the action of bacteria, fungi, enzymes and chemical action and to meet demand during the rest of the year when the fresh product is not available.

Various technologies exist for the preservation of food stuffs: canning, refrigeration and dehydration, to mention a few. Drying or dehydration is the longest established and the most common method of food preservation in rural Zimbabwe. The range of commodities being preserved is very wide: grain crops (eg maize), leaf vegetables (eg cowpea leaf), fish (eg kapenta), meat and many others. Sundrying in which the commodity to be dried is simply spread in the sun (after varying pretreatments) is the least sophisticated.

### **PROBLEMS WITH CURRENT DRYING TECHNIQUES**

- (a) When crops are left in the field to dry losses occur from the action of vermin and from possible rotting caused by re-wetting from rain. A survey (Wellan 1972) showed that losses as high as 10% are common.
- (b) Sun drying is slow and inefficient. There is a real danger that the product can spoil before it dries. This is especially problematic with fish, and any unfavourable weather can result in a big catch going bad.
- (c) Direct exposure to the sun, normally the practice, results in considerable loss in nutritional value of some commodities like vegetables. An analysis

on some traditionally dried vegetables in Harare carried out by the Food Science Department of the University of Zimbabwe showed that there is a marked drop in nutrients (vitamins and proteins) during the drying process. Yet dried vegetables continue to constitute a significant proportion of the diet in rural areas during the dry season.

The need for the artificial drying in order to reduce post-harvest losses and to improve the quality, thus, becomes immediately obvious. The critical shortage of firewood and the high prices of other fuels, leave solar energy as the cheapest energy source. However, harnessing of solar energy for crop drying is a fairly new technology especially in developing countries.

### **SOLAR ENERGY FOR CROP DRYING**

Solar dryers, mostly of the roof sandwich type, have been constructed and tested for the drying of maize, tobacco, lucerne and coffee (Radajewski 1979, Johnston 1979). Since these dryers employ electrically driven blowers to force the hot air through the drying commodity, they were considered unsuitable for rural areas for the following reasons:

- (a) electricity is not readily available in most of rural Zimbabwe,
- (b) most farmers in the rural areas are poor and cannot afford (individually) the high capital and running costs, that would be involved in a scheme of this nature,
- (c) drying in rural areas is generally done on a small scale.

A project directed specifically at the poor rural farmer in which dryers for small scale drying and relying on natural convection are envisaged has been launched. The project has the following objectives:

- (a) To evaluate the need for and the technical feasibility of solar drying in order to conserve and extend the food supply to meet the demand when the fresh commodities are not available.
- (b) To design, fabricate, test and develop a simple solar air heater that is efficient, inexpensive and easy to construct. The solar collector must be made from locally available material where possible and must have low maintenance. The dryer must rely on natural convection for its operation. Modification and adaptations will be made on some dryer models tried elsewhere.
- (c) To develop drying methods and apply these to a range of products selected after some pre-screening tests. The method which must be simple and result in maximum retention of food nutrients during drying and a product with a long storage life.
- (d) To disseminate the optimised dryer models and drying technology to the rural areas of Zimbabwe.

### **PROJECT STAGES**

The project has been envisaged in three phases:

### **Phase I**

Resources base identification and evaluation. This includes:

- (i) evaluation of available literature.
- (ii) compilation and evaluation of climatic data of Zimbabwe: solar radiation, temperature, relative humidity, etc.
- (iii) identification and evaluation of existing drying technologies, products being dried and problems met.
- (iv) seasonality of crops, etc.

### **Phase II**

Experimental works:

- (i) Development and optimisation of dryer models, drying methods and storage methods.
- (ii) Quality evaluation of the dried commodities.
- (iii) Field testing of optimised dryer model in selected locations.

### **Phase III**

Extension and follow-up.

## **REVIEW OF PROGRESS ON THE PROJECT**

- (a) A collaborative network of the Government Ministries of Energy, Agriculture, Community Development and Rural Development and with the University of Zimbabwe has been established. The University of Zimbabwe will play a vital role in the technical aspects of the project by providing laboratory facilities for physical evaluation of dryers and for biochemical analysis of the dried commodity. The other Government Ministries will give field support in the experimental as well as the extension stages of the project.
- (b) Data on the climate of Zimbabwe has been collected and evaluated. The results can be summarised as follows:
  - (i) The mean annual daily total of radiation over Zimbabwe is about  $20\text{MJ/m}^2$  per day and for 275 days of the year there is bright sunshine for six to eight hours per day. The summer values of radiation are as high as  $24\text{MJ/m}^2$  per day and winter  $16\text{MJ/m}^2$  per day.

The Victoria Falls - Binga - Kariba region receives the highest radiation followed by the southern low-veld (Buffalo Range, Chiredzi, Beitbridge). Lowest radiation is received in the Eastern Border Regions of the country.

- (ii) Mean annual temperatures vary around 18-19°C at 1,400m above sea level, with highest values (23°C) in the low-veld (Kariba - Victoria Falls and Buffalo Range - Beitbridge). Coolest temperatures (15°C) are experienced in the Eastern Districts.
- (iii) The western half of the country experiences the driest weather, recording the lower average relative humidities in the country. The most humid weather is experienced in the Eastern Districts.

Minimum relative humidities are experienced in September/October and maximum values in February. On a diurnal scale, maximum relative humidities are experienced around 14 hrs.

From the above, it can be concluded that Zimbabwe, with the exception of the Eastern Border regions which receive minimum radiation and experiences highest relative humidity, has a very good potential for use of solar energy for crop drying. Temperature fluctuations are not severe and there is no serious threat of frost.

- (c) A survey was carried out to identify products currently being dried, their regional, seasonal distribution and also current drying practices. A questionnaire was prepared which solicited for the following information:
  - (i) name of product
  - (ii) how the product is prepared for drying, eg cleaning, shredding, etc.
  - (iii) drying season
  - (iv) method of drying
  - (v) how long the product takes to dry on average
  - (vi) how much of the product is dried at any one time
  - (vii) how the dried product is stored for later use
  - (viii) for how long the product can keep before deteriorating
  - (ix) how the product is prepared for eating
  - (x) problems, comments, etc.

The result of the survey can be summarised as follows:

- (i) The range of products being dried was found to vary little from one region to another except for fish which are from the Lake Kariba shores or the Zambezi River.
- (ii) The drying season ranged from late December to May/June (ie the rainy season).

- (iii) Drying practices involved mainly:
- spreading the product in the sun (or shade) after cleaning, shredding and (sometimes) boiling;
- in few cases, steaming followed by direct exposure to the sun.
- (iv) The dried product was used mostly for own consumption except for fish, cowpea leaves, okra and edible caterpillars which were for both own consumption and for sale. The tendency to produce for sale is greater around big towns where a ready market is found from the townspeople.
- (v) There was little mention of the major grain crops, eg maize, from the list of products being dried for preservation. Perhaps this was because the harvest time for maize, (April/May/June) comes at the end of the rainy season and relatively fewer problems are experienced in having these dry than for the other commodities. However, recently, a request for artificial drying of sorghum so the crop can be harvested earlier and protected from birds - birds being the biggest threat to maturity of sorghum - has been made.
- (d) Visits have been made to potential field testing sites at Mrondera, Gwebi, Chiredzi and Nyanga and formal preparations are underway for setting up experimental dryer units.

### **FUTURE ACTIVITIES**

Future programmes in the project can be summarised in the following broad tasks:

- (a) setting up of experimental dryers units followed by development and optimisation of the same.
- (b) developing and optimising drying methods and quality development of dried products.
- (c) disseminating the optimised dryer models and drying methods to the rural areas with assistance from extension agents.

### **CONCLUDING REMARKS**

The climate of Zimbabwe is generally suitable for active utilisation of solar energy for crop drying. Traditionally, drying as a means of preserving food is an established practice. The task of this project is to introduce faster and better drying methods in order to:

- (a) reduce harvest losses, eg through early harvest of sorghum
- (b) improve on nutrient retention of the dried product especially vegetables
- (c) generally extend availability of protein and vitamin foods into the dry season so as to improve the diet of the people.

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**REPORT OF TESTS ON USE OF SOLAR-TENTS  
FOR FISH DRYING IN THE GAMBIA**

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**ABSTRACT**

A substantial amount of the total annual landings of fish in the Gambia is sundried and this paper discusses the use of solar dryers for this purpose. Solar-tent dryers appear to have considerable promise particularly in terms of costs when local and low-cost materials are used for their construction. But, further work should be carried out to improve durability of the dryer, increase the loading capacity and improve its drying efficiency.

**INTRODUCTION**

The main problem that prompted research on the use of solar dryers for drying fish in the Gambia is the extent to which losses are encountered. Although attempts have never been made to systematically quantify losses, numerous and various observations suggest losses appear to be quite high and insect infestation prevalent, particularly during the rainy season.

Fish drying is an age-old tradition in the Gambia as in many African countries. Fish are commonly fermented prior to sun-drying on low wooden racks, the ground or rocks. Salting and drying are used in conjunction, but there are several problems and the products obtained are of low quality and short storage-life.

In an attempt to alleviate problems associated with losses in dried fish production the use of solar dryers has been investigated. This research is seen to directly correspond with government's development priorities, especially those aimed at increasing food production, and in particular, protein - food supplements, by way of preventing post-harvest losses.

Dried fish production has considerable potential in the country. In 1983, about 500 tonnes of cured fish were exported to neighbouring countries and Asia. About half of this was dried-salted fish and fishery products. The Catch Assessment Survey of the Fisheries Department has indicated that a total of 8455.5 tonnes were landed in 1983 by 'marine' (Atlantic Coast and low river) artisan fishermen, Demersal species account for 1952.2 tonnes of this total of which it is assumed that all the cassava fish (Otolithus typos) sharks and rays were sun-dried. The estimated total weight of cassava fish landed was 296.1 tonnes and of sharks and rays 376.9 tonnes. It is also assumed that 45-50% of the balance of 1658.1 tonnes of landed demersal fish would have been sun-dried within the year. Since only a small amount of this catfish (Arius Spp.) is normally smoked for local marketing, it is estimated that at least 60% of the 765.5 tonnes landed in 1983 was sun-dried mainly for export to neighbouring countries. Sea-snails are sun-dried all year round but data on the amount is not available.

This probably underestimates production. Large quantities of dried fish and fishery products are suspected to leave the country unrecorded each year.

This project has been undertaken, with a view to improving fish drying technology by using solar dryers constructed with low-cost and locally available materials to reduce losses in cured fish production.

### **OBJECTIVES**

The objectives of the research are both short-term and long-term.

- (a) The short-term objective is to conduct investigations on the use of solar-tents for drying fish, using low-cost, locally available materials to prevent infestation and reduce losses.
- (b) The long-term objective is to carry out essential extension services whereby the use of solar dryers will be demonstrated to local processors and fishermen who will be encouraged to use such facilities throughout the country.

### **PROJECT ACTIVITIES**

The research programme encompasses the construction of solar dryers; drying fish of different species and performing subsequent laboratory analysis, (ie moisture, ash, lipid and protein contents).

At the inception of work, solar tents of various dimensions were constructed but all had the same design: 2m (h) x 2m (L) x 2.5, (w); 2.5m (h) x 4m (L) x 3m (w); and 2.5m (h) x 6.3m (L) x 6.3m (w). The former was capable of drying about 15-20 kg; the second about 40-45 kg and the third 400-500 kg. Drying time for a satisfactorily dried product was about 3 days for all the dryers.

All fish samples were obtained frozen from factories, gutted and brined for about 16 hours. As brining is noted to be more effective than sprinkling salt on fish, it was the only salting method applied during the trials. The species used were mostly demersal fish and include the families Sciaenidae, Polynemidae, Scrombidae and Pomadasysidae.

Laboratory analysis of wet and solar dried samples were performed, but the solar dried samples tested were all obtained from the tent with the smallest dimensions.

Various kinds of locally available materials were tried in an attempt to reduce cost and/or to improve the durability of the dryers. Imported wood was used for the construction of the first tent and 'rhun' palm sticks for the second and third.

Initially, officials of the Department were solely involved in the trials, washing, gutting, descaling, salting and drying fish. After obtaining some results and scaling up the design of the tents more fish was needed to load the dryers fully and at this stage local processors were integrated into the project.

The technical staff comprised of a Senior Fisheries Officer, Fisheries Field Assistants and a carpenter. There was no written timetable as fish were obtained periodically from factories, and later, from artisanal fishermen, dried for 2-3 days and stored at room temperatures. Experiments were conducted for a period of 6 months using the smallest size dryer, and after that time, extension services were launched involving local fishermen and processors thereby examining some possible approaches most appropriate in technology transfer of this kind to the Gambian fishing communities.

No techno-economic feasibility studies were carried out but experience has so far hinted that this type of venture can be viable mainly because:

- (a) Products can be dried within a short period allowing more to be produced than when sun-drying.
- (b) The number of individual pieces in a given batch for solar drying remains the same at the end of the drying time, whereas, the sun-drying the number of individual pieces started with is reduced at the end of the drying time due to severe infestation by maggots.
- (c) The solar tents are cheap and easy to construct (cost of one is about D200-D300) and take only a few hours with little labour to construct once the materials are available on site.

#### **PROBLEMS WITH THE SOLAR-TENT DRYER**

- (a) Procurement of appropriate materials such as UV resistant polythene in developing countries like the Gambia is difficult at times.
- (b) The polythene covering the tents is delicate and extreme care must be taken always during operations to prevent damage. Thunderstorms are potential hazards to the dryers.
- (c) Durability of the dryers needs improvement especially the netting on the air vents. These tend to tear easily after contact with 'salty air' from the sea.
- (d) The position of the drying racks on the sides of the tent, beneath which lie the black collectors, may cause sun-rays reaching the fish spreading on the racks before reaching the collectors below, and hence reduce the efficiency of the dryers. This situation might have contributed to case-hardening problems encountered during trials.
- (e) Local processors must be educated to use the facility correctly by ensuring that the air-vents are utilised properly during operations to give enough ventilation at the initial drying stage and help reduce case-hardening problems.

#### **RESEARCH METHODS AND ANALYTICAL PROCEDURES**

Various species of fish were descaled, gutted, brined and dried in solar tents. From each species 5-7 gms of flesh was removed from representative samples and the laboratory analysis for moisture content, ash and lipid were carried out. It is worthy to note that samples tested during these laboratory exercises were obtained from the solar-tent with the smallest dimension. All the exercises could not be performed for all the species due to lack of certain apparatus and chemicals.

#### **Determination of moisture content**

- (a) Moisture dishes with a layer of acid-washed sand in the bottom were left to dry overnight in an oven at 105°C. Removed from oven and placed in a dessicator for 30 mins to cool. Then weighed on an analytical balance ( $W_1$ ).

- (b) About 2.5g of representative sample of flesh was homogenised and placed in dishes and re-weighed ( $W_2$ ). All samples were in duplicate. Dishes were returned to the oven and left overnight. They were then removed from the oven and again desiccated for about 30 mins to cool and re-weighed ( $W_3$ ).
- (c) Percentage moisture calculated thus:

$$\text{moisture} = \frac{(W_2 - W_3) \times 100}{W_2 - W_1}$$

#### Ash determination

- (a) About 1.5kg of sample was weighed and placed in labelled crucibles which were pre-weighed when empty.
- (b) The contents were charred under bunsen burner flame and placed in a furnace.
- (c) After 30 minutes the samples were placed in a desiccator for about 20-30 minutes.
- (d) Crucibles were re-weighed and the percentage ash content calculated:

$$\% \text{ ash} = \frac{\text{weight of ash}}{\text{weight of sample}} \times 100$$

#### Lipid determination

'Soxhlet' extraction method was used.

#### Protein determination

'Kjeldahl' method was applied but only a single trial was performed due to lack of chemicals.

### RESULTS

**TABLE 1: Change in % moisture content during solar drying**

Drying times in O. hrs	Species					
	<i>O. senegalensis</i> (Ngouka)	<i>P. jubelini</i> (Sompat)	<i>Epinephelus</i> sp (Choff)	<i>Cranx</i> sp (Sacca)	<i>Scomber</i> sp (Njunna)	<i>Sardinella</i> spp (Yaboi)
0	79.3	79.9	78.9	72.2	76.6	75.1
7	51.4	43.3	42.6	47.6	52.2	26.9
14	32.9	30.0	31.4	34.8	36.6	21.5
20	25.2	23.3	24.1	27.3	27.3	21.5
28	19.1	20.0	20.5	22.3	22.3	13.3

**TABLE 2: Changes in weight (kg) during solar drying**

Drying time in hrs	Species					
	Ngouka	Sompat	Choff	Sacca	Njunna	Yaboi
0	0.27	0.30	0.43	0.40	0.79	0.13
7	0.20	0.19	0.38	0.30	0.69	0.08
14	0.13	0.17	0.21	0.25	0.49	0.06
20	0.14	0.15	0.19	0.22	0.36	0.06
28	0.12	0.12	0.17	0.20	0.27	0.05

**TABLE 3: Chemical composition of wet fish samples**

Species	%	%	%	%
	Moisture	Ash	Lipid	Protein
Ngouka	79.3	1.54	0.97	-
Sompat	79.9	1.72	0.44	-
Choff	78.9	1.60	1.02	-
Sacca	72.2	1.60	1.14	-
Njunna	76.6	1.99	2.07	-
Yaboi	75.1	1.97	3.69	-

**TABLE 4: Chemical composition of solar dried samples**

Species	%	%	%	%
	Moisture	Ash	Lipid	Protein
Ngouka	19.1	20.1	-	-
Sompat	20.0	15.5	2.5	-
Choff	20.5	14.9	3.2	-
Sacca	22.3	-	-	-
Njunna	22.5	19.3	6.08	43.0
Yaboi	13.8	-	-	-

## **DISCUSSION**

As indicated in the data provided, the ash and lipid contents of each species increased after drying. This, however, is assumed to be a relative increase as the total amount of these compounds remain unchanged. As a substantial amount of water was removed during drying this relative increase was observed. The increase in ash content is also a result of additional minerals taken into the fish flesh during brining.

Due to the deficiency in laboratory equipment, chemicals and other materials all intended analysis could not be carried out. The brine-strength was not measured because of lack of hydrometers.

Samples that were selected for storage trials were kept under ambient temperatures. Some were packaged in sealed plastic bags, others were left exposed. Those in the plastic bags were brittle but still of good edible quality after 6 months storage. The mackerel (Njunna) and sardinella (Yaboi) had, however, developed a somewhat rancid taste during storage. The exposed samples were mouldy and were infested with Dermestes beetles.

Apart from the sardinella all the other samples were sliced into pieces of various sizes. The sardinella samples were left as whole fish because these were small size individuals. This might have contributed to the achievement of low moisture content, as low as 20% within 28-30 hours in these species, because the thinly sliced or small whole fish have large surface area relative to their masses, and as such, this will speed the rate of diffusion by decreasing the distance from the centre of the fish flesh to its surface.

Observations have shown that the "Falling rate period of drying" (ie the phase at which the rate of movement of moisture to the surface of the fish is reduced and the drying rate becomes slower) is significantly shortened when the solar tents were used. This caused a tremendous reduction in the overall drying time especially when the small size fish were used in the trials.

Although some limitations have been observed in the use of solar-tent dryers, results obtained from these trials have been encouraging. The internal temperatures of the dryer are usually lethal to flies which occasionally enter, and products obtained are of good, clean and well-dried quality. During the trials only a few maggots were observed infesting the fish samples in the dryers. However, because the sample dealt with throughout the trials was less than a kilogram, the absence of heavy insect infestation could be understood not only as a result of the effectiveness of the dryer, but also that small quantities of wet fish attract fewer flies. More maggots were observed in fish in the larger dryers but these did not cause significant losses.

The major limitations in the use of solar-tent dryers for fish drying are:

1. Clear UV-resistant polythene and plastic mesh may be difficult to procure in developing countries like Gambia, and to improvise substitutes might not be an easy thing to do.
2. The construction technique, particularly in cladding the structure, needs improvement to improve the durability of the dryers.
3. Care must be taken at all time during operations as the plastic is delicate.

This report concedes that despite these problems, the use of solar-tent dryers for fish could be a vital factor in the development of our traditional drying technology. Acknowledging that about 35-75% of the wet fish landed by artisanal fishermen get spoilt or stale at landing or before reaching intended markets; and that all these spoilt fish must be dried to prevent further losses, the use of solar dryers as an improved technology should be highlighted.

It is a generally accepted view that the introduction of any new technology in developing countries is usually met with problems and constraints that are fundamentally socio-economic. For instance, traditional fish processors are especially obsessed with the weight of their products and prefer dried fish with some amount of moisture enough to give more weight and more money when marketed on wholesale basis. Hence, it is difficult to persuade processors to leave their fish in the dryers to dry to low moisture contents (ie as low as 20%). Consequently, if the application of solar dryers for fish is to fulfil its objectives under these circumstances, advice on improvement on packaging and storage methods using locally available, low-cost materials should be the follow-up to solar drying exercises to help prevent losses after processing.

It cannot be urged that the solar tent is not the ultimate design for a fish solar dryer. But, so far, it has shown considerable promise and should be given time and thought for modification to increase its capacity, efficiency and durability.

### **CONCLUSION**

The results of this research programme will be used by officials of the department as a basis for giving proper advice to local processors and promoting the use of solar tents in traditional fishing communities.

As the tents are cheap and easy to build the prospects for socio-economic cost-effectiveness are bright and should be investigated in-depth to give a broader perspective of solar drying in the Gambia. It is thought that once durability is enhanced the solar tent would become more attractive to local processors who may then invest in procuring the facility with the assistance of the Department.

Even though people have realised the effectiveness of the dryer, especially when used during the rains, most of them may not consider it worthwhile to search for materials and invest in one because other essential materials such as the UV resistant polythene and plastic mesh are not readily available in the country. It is important to note that, along the marine coast fishery women are the main persons engaged in fish drying and their present socio-economic status does not provide them with strength and funds to be able to procure all the needed materials and contract a carpenter to build the dryers. In this case, it is thought that the Fisheries Department should be intimately involved in assisting processors to set-up drying yards with related facilities and thereby arrange with these end-users to remit the cost incurred in instalments as agreed by the parties.

The social compatibility of the facility for the intended end-users is unquestionable. However, the people will also be more responsive to the idea if assistance is given to them by organising them into small associations at each site; providing the facility in the form of a fenced drying-yard with few tents, a platform for gutting, descaling and cleaning; a tank for salting and fermenting fish, and a small-size store. This, it is envisaged, will render the people a good sense of belonging and a chance to do something new and different on a collective basis to improve their lot.

### **RECOMMENDATIONS**

- Experiments on packaging and storage, using locally available, low-cost materials to reduce beetle infestation and subsequent losses should be conducted to align with improvement in drying technology.
- As transportation problems are not uncommon in the country, dried fish products destined for upcountry marketing or export should be appropriately packaged and stored to avoid losses.
- In line with Government's policy to improve the nutritional standard of Gambians and generate more financial benefits within the artisanal sector, this project has been seen as a potential source of boosting the cured fish trade; diversify the development strategies for the artisanal fisheries sector, and amongst other things, provide employment opportunities for nationals, especially the women.

To this end, it appears that there is a pressing need for more cooperation between the Gambia and participating countries; provision of funds and materials not only to construct dryers, but, to also build accompanying facilities such as platforms etc, and be able to purchase small amounts of fish to demonstrate to intended end-users how to use the facilities and prevent losses.

### **ACKNOWLEDGEMENT**

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The cooperation of the Director of Fisheries, Fisheries Assistants Messrs A Mendy and M Njie are greatly acknowledged for without their enthusiasm and diligence the project would not have been carried out smoothly.

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## **SOLAR FISH DRYING PROJECT IN MOPTI (MALI)**

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### **INTRODUCTION**

In Mali, fishing is a traditional occupation for more than a hundred thousand people living on the banks of the rivers Niger and Senegal. Fishing production attains 100,000 tons per year. Because of the lack of means of refrigeration to store fresh fish or transport it, most of the fish is dried or smoked. The traditional drying process consists of laying fish on sand or straw on the banks of the river and letting it dry under direct sunshine. This process is lengthy (5 days or more) and leaves fish vulnerable to insect attack and dust. Fish losses during this process can be as high as 50-60%!

In order to improve hygienic conditions of this drying process and reduce fish losses, the Solar Energy Laboratory of Bamako (LESO) and a fishing development organisation called "Operation Peche Mopti" (OPM) set up a project to introduce improved solar drying. This project has received support from the "International Development Research Centre" (IDRC) from Canada. A survey was initially conducted in fishing villages to determine needs. This survey resulted in the definition of three types of dryers requested to meet the needs expressed: a natural convection stationary dryer for permanent fishing villages, a natural convection mobile dryer for temporary fishing villages, and a forced convection dryer for the OPM office. After this survey a research programme was set up and resulted in the development of a tent dryer, a TAOS dryer and a 150 kg forced convection dryer. These prototypes, after full testing at laboratory level, have been installed at the OPM office and two fishing villages. Field monitoring was performed, and as a result, the tent dryer was abandoned, improvements were done on the TAOS dryer to prevent dust settling on the fish, and the forced convection dryer proved to be usable for other purposes, such as reprocessing of wet smoked fish. Results of laboratory testing and field monitoring are given in the paper.

### **CHOICE OF SYSTEMS**

The choice of systems is based on our own experience and on that of the neighbouring countries' research centres (primarily Senegal), as well as on technical and economic criteria.

For permanent fishing villages, we have chosen as dryer, the dryer-tent inspired by models tested by the Institute of Food Technology at Dakar (Figure 1). This was motivated by the simplicity of the system, the possibility of using local materials (for example, bamboo) and the low cost.

For temporary fishing villages, our choice was the solar dryer TAOS, made by GATE (GTL) and which has mainly been tested in Latin America. This dryer is simple and small, which eases transport from one place to another by pirogue (fishing boat) for example: that is what justifies the choice. In addition, it can be easily copied by pirogue builders using wooden planks (Figure 2).

For OPM's head office, we have chosen a solar dryer equipped with an electric ventilator. This is placed in the roof to avoid any problems of shadows. The ventilator has a flow shutter which can effect the temperature of the interior of the drying cabin (Figure 3). The dryer has a capacity of 150 kg and can easily be doubled up to meet the estimated OPM needs of up to 300 kg. The possibility of regulating the interior cabin temperature through flow rate adjustments means that the dryer could be used for treatment of dried or rehumidified smoked fish. At the moment, OPM uses archaic ovens, which burn a great deal of wood.

### **LABORATORY TESTING**

The laboratory tests are mainly concerned with forced convection drying, as we found plenty of experimental data on the other two systems: the dryer-tent and the TAOS dryer.

#### **Description of the forced convection dryer (SCF)**

The initial diagram of the SCF is given in Figure 3. The roof panel is made of 9 collectors (3 series of 3). Each collector has a working area of  $1.55\text{m}^2$ , which means the entire panel has a working area of  $13.95\text{m}^2$ . Figure 4 gives the collector diagram. Air circulates above and below the absorber before entering the isolated drying cabin. Two ventilators with shutters upstream of the cabin vary the rate of flow from  $638.27\text{m}^3/\text{h}$  to  $1,485.71\text{m}^3/\text{h}$ .

#### **Test procedure**

Tests are carried out in outdoor conditions on several consecutive days. The thermocouplings were placed in different sections of the dryer (Figure 3) and the temperatures were read from 8.30h to 17.30h, at one hour intervals, by an Omega Data Logger.

The solar radiation on the collector surface was measured and integrated by a Haenni pyranometer and integrator.

The tests were run under no- and full-load conditions.

### **Results and discussions**

#### **Test under no-load conditions**

Figure 5 gives the curves of temperature variation at different points in the dryer on a typical day. The average temperature in the cabin,  $T_{4,m}$ , is obtained by adding the different values measured of  $T_4$  and dividing them by the number of times measured. The average temperature increase in the collector  $(T_3 - T_2)_m$ , is obtained by adding the differences  $(T_3 - T_2)$ , and dividing them by the number of times measured. From the global radiation on the collector surface, given in  $\text{Wh}/\text{m}^2$ , the average strength of the global radiation was obtained in  $\text{Wh}/\text{m}^2$  by dividing this amount by the length of time of the solar intensity.

Thus, from the experimental data, we were able to show (Figures 6 and 7), the variation of  $T_{4,m}$  and of  $(T_3 - T_2)_m$  with respect to the average intensity of the solar radiation (Figure 6) and with respect to the rate of flow (Figure 7).

It can be seen that the average temperature in the dryer and the average temperature increase in the collector rise with the average intensity of the solar radiation and lower when the rate of flow increases.

### Test under full-load conditions

For the full load testing, 50 kg of scaled headed and eviscerated fish were placed in the dryer. The tests took place from 8h to 18h and periodically the temperatures were taken and fish weighed. The amount of incident of solar radiation was measured by a Haenni pyranometer coupled to an integrator. The fish stayed in the dryer overnight with the ventilators closed.

The test lasted 4 days. The final weight of the fish was 15.89 kg, that is 32% of the initial weight, which is within the limit of 25-35% recognised by the OPM. Figure 8 gives the drying curve.

During the test, we noticed the development of maggots on the fish from the second to the third day. However, on the fourth day, due to intense solar radiation producing temperatures of more than 50°C, the maggots were removed. The drying had taken place without any previous chemical treatment of the fish.

This proved that the forced convection dryer was suitable for fish drying.

### TESTS ON SITE

For the tests on site, a dryer-tent and two TAOS dryers were installed in the fishing village of Sense near Mopti, and a forced convection dryer was placed in the fishing port of Mopti at the OPM head office. The following results were obtained:

#### Dryer-tent

The dryer-tent could not be used by the fishermen because of tears in the transparent polyethylene cover caused during installation by very strong wind. The dryer was finally destroyed by tornadoes.

Following this unfortunate experience, it was decided to abandon that system.

#### TAOS dryer

After installation, the TAOS dryers were used daily by the fishermen: about 60 kg of fish were dried per week per dryer, in spite of the shortage of fish in the area. The Sense Fish Inspector regularly conducted performance tests on the dryers. Figure 9 gives a typical drying curve produced by the Inspector, which indicates the following benefits from TAOS dryers:

- shorter drying time;
- better quality of dried fish;
- no insect attack;
- increased quantity of dried fish in comparison to drying in open air (less loss during drying).

The Inspector did, however, underline the negative effect of dust-bearing wind which blows into the dryer and settles on the fish.

The fishermen were satisfied with the dryers: in fact the fish dried there was of greater quantity and, above all, is a product which sells quickly because of its good quality. However, they did not approve of the small capacity of the dryer.

The Inspector then tested the transportation of the dryer by pirogue. The test showed that the dryer could easily be put on the roof of the pirogue; however, the fishermen had wanted a dryer which could be completely dismantled.

### **Forced convection dryer**

Installed at the OPM head office, this dryer was mainly for use in re-drying dried or smoked fish which arrived at the port of Mopti. During stocking and transport, the dried or smoked fish reabsorbed humidity and re-drying was necessary before selling. Equally this destroys the maggots on the fish.

OPM has hitherto used ovens which burn a great deal of wood for re-drying, something of increasing scarcity in the area of Mopti. A test run with gas-oil oven failed because of cost and poor performance (fish breaking and smelling of gas-oil).

Figure 10 gives the curve obtained during re-drying of an experimental load consisting of 31.32 kg of dried humid fish and 10.57 kg of smoked humid fish. The re-drying lasted 3 days. The weight loss was 17% for the dried fish and 25% for the smoked fish. The fish was completely clear of maggots, and was considered to be of very good quality by the OPM agents.

### **CONCLUSIONS**

The main conclusions which can be drawn from the work carried out as described earlier, are as follows:

- a) the transparent polyethylene available in Mali is not sufficiently strong for the climatic conditions there, which limits the possibility of using dryer-tents, in spite of their low cost;
- b) the TAOS dryers are well adapted to the needs of the fishing villages; they produce very good quality dried fish in a shorter period of time without loss of weight due to insects; in addition they can be transported by pirogue which makes them suitable for travelling fishermen; the problem of dust can be solved by turning down the air inlet and outlet to protect them from the wind: this is in the process of being tested;
- c) the forced convection dryer is as good for drying as for re-drying of fish; by using it, the OPM could save the wood used up to now for re-drying; the use of photovoltaic baskets to provide electric energy for ventilators makes this system completely independent of the normal sources of energy, so it can be used in areas without electricity.

### **ACKNOWLEDGEMENTS**

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FIGURE 1: Closed dryer

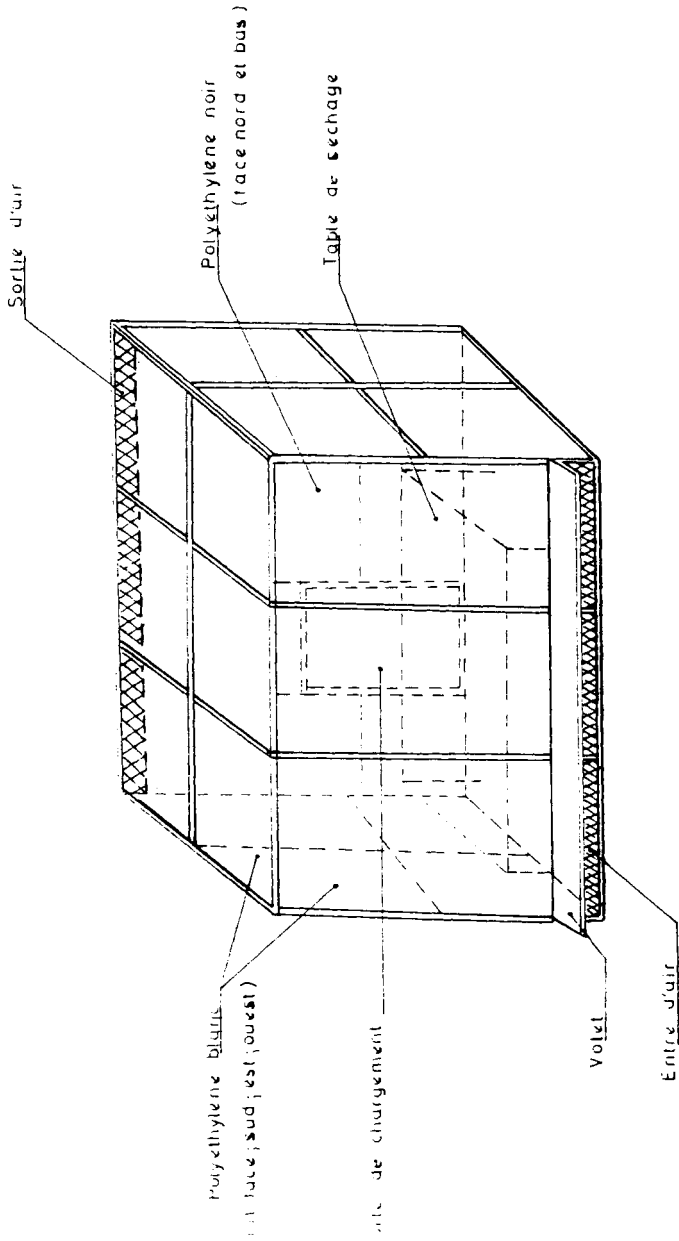


FIGURE 2: TAOS dryer

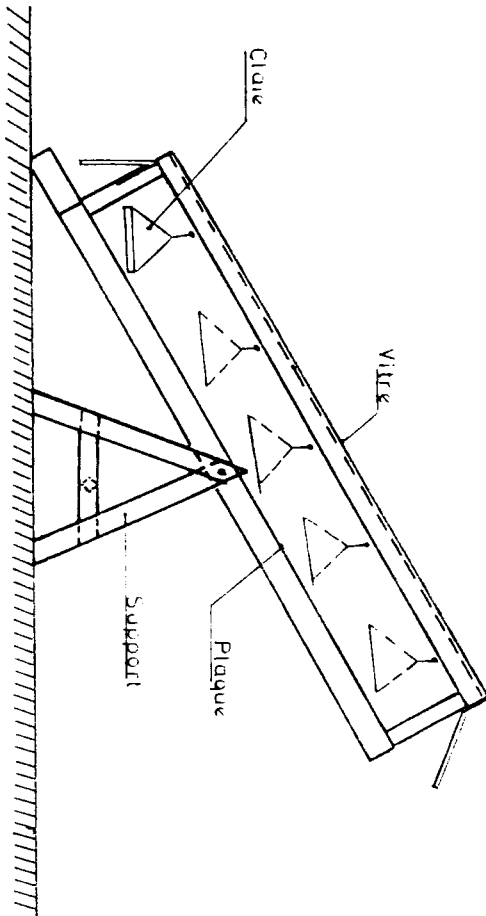


Fig:2 SECHOIR TAOSI

FIGURE 3: Section of forced convection dryer

- 11 PLAQUE
- 12 ENTREE AIR FRAIS
- 13 " " CHAUD
- 14 INTERIEUR CABINE
- 15 SORTIE AIR CHAUD

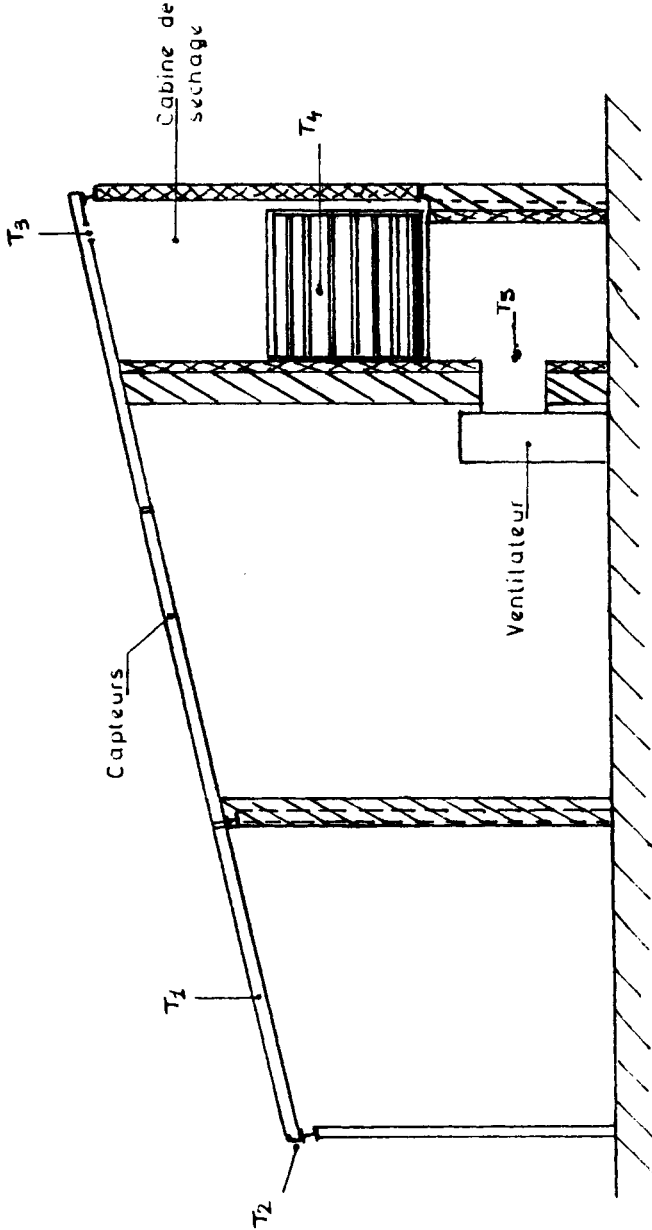
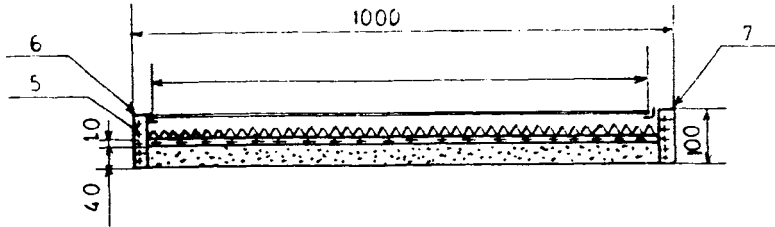


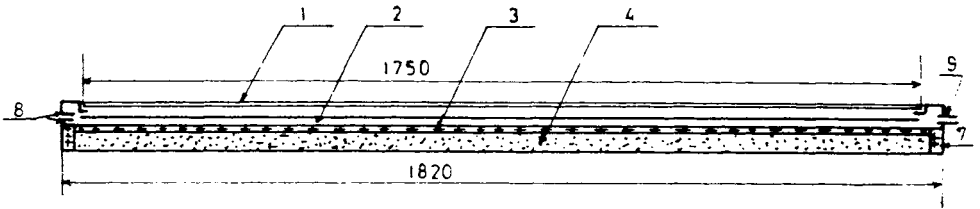
Figure : 3 COUPE DU SECHOIR A CONVECTION FORCEE

**FIGURE 4: Sections through a hot air receptor**

Echelle 1/10



**Transversal section**



**Longitudinal section**

- |                               |                   |
|-------------------------------|-------------------|
| 1. Vitrage                    | 6. Forme laterale |
| 2. Plaque                     | 7. Forme frontale |
| 3. Isolation (laine de verre) | 8. Embout femelle |
| 4. Plaque polystyrene         | 9. Embout male    |
| 5. Laine de verre             |                   |

Surface utile: 1,60m<sup>2</sup>

FIGURE 5: Typical temperature variations in dryer over operating day

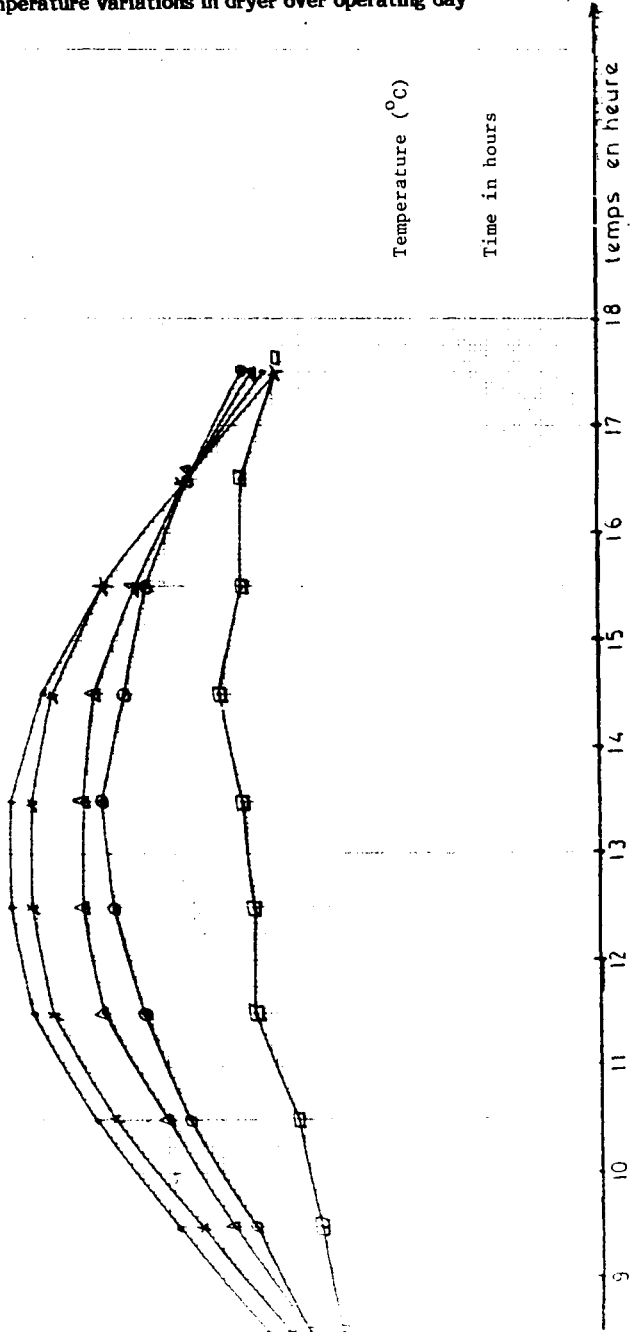
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FIGURE: 5

FIGURE: 5

$H = 6, 14 \text{ kWh/m}^2$   
 $Db = 1091, 5 \text{ m}^3/\text{h}$

- $T_1$  cover temperature
- $T_2$  cold inlet air temp
- $T_3$  outlet air temp
- $T_4$  cabin interior temp
- $T_5$  hot air exit temp



Temperature (°C)

Time in hours

18 temps en heure

FIGURE 6: Variation in the average temperature in the dryer and average temperature increase in the receptor due to solar intensity

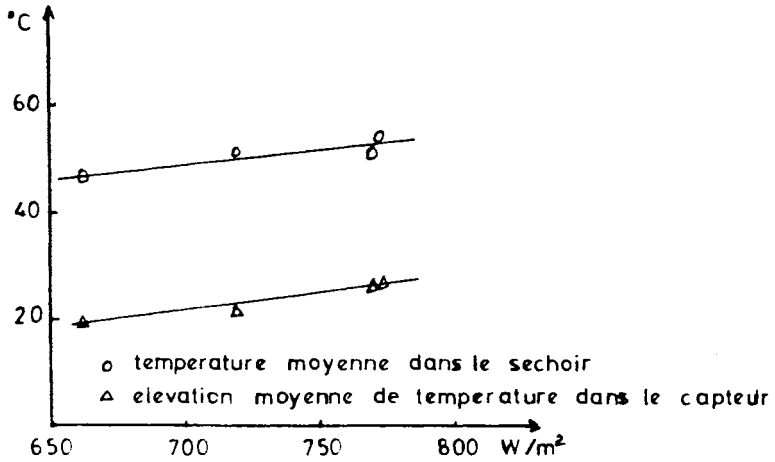


FIGURE 7: Variation in the average temperature in the dryer and average temperature increase in the receptor due to the rate of flow

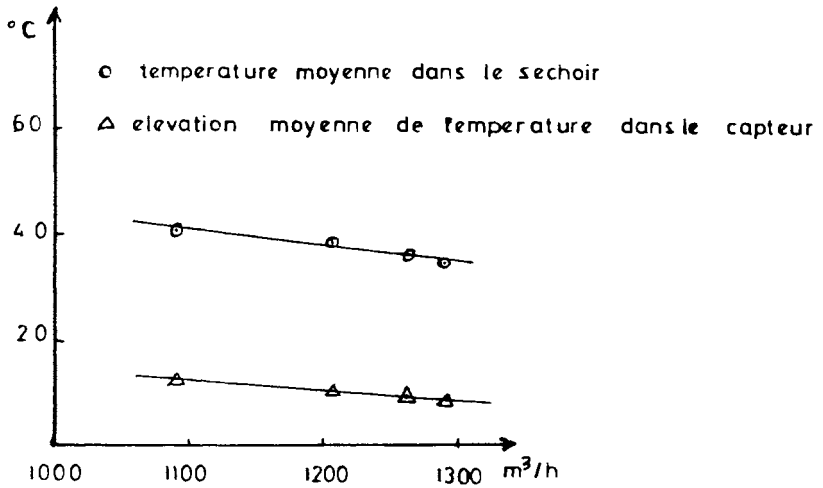


FIGURE 8: Drying curve of fresh fish in the forced convection dryer

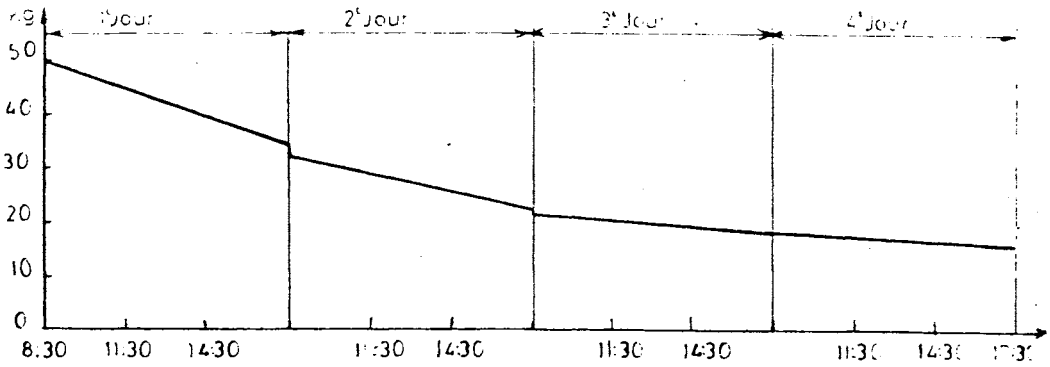


FIGURE 9: Drying curve of fresh fish in the TAOS dryer

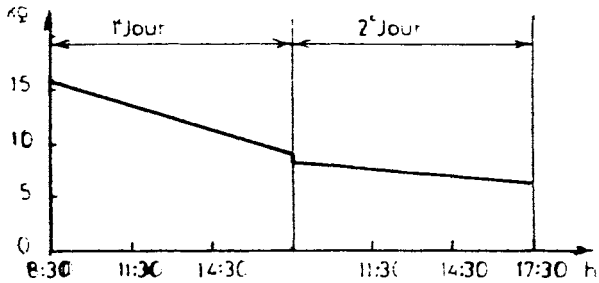
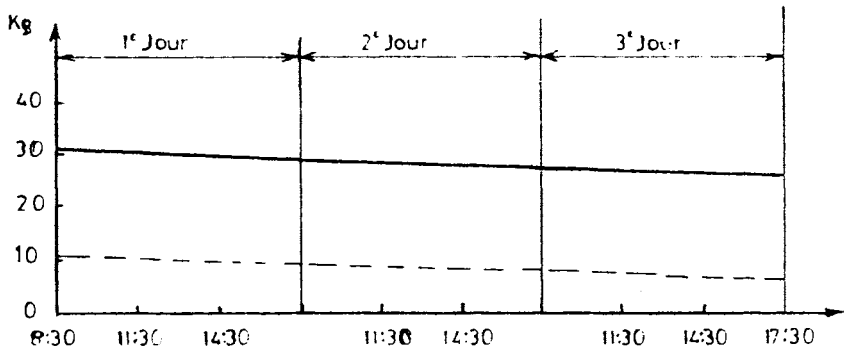


FIGURE 10: Re-drying curve of dried fish (full treatment) or smoked fish



## **B. SOLAR THERMAL**

## **SOME LOW COST RESEARCH TECHNIQUES FOR USE IN DEVELOPING COUNTRIES**

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### **ABSTRACT**

Research of renewable energy is capital intensive. Many important research tools are out of the reach of many researchers in developing countries. This paper discusses some research equipment and techniques which can be acquired and implemented at relatively low cost.

### **INTRODUCTION**

The oil crisis of 1973 produced, among other things, a tremendous upsurge in research on renewable energy sources, particularly solar and wind energy. Although the initial impetus has somewhat abated, much research is currently in progress in many countries of the world, including the developing countries. However, research is capital intensive and some of the important research tools and equipment like solar simulators, computing centres and data acquisition and processing systems are often beyond the limited facilities of some researchers in developing countries.

In this paper, examples are given of low cost research undertaken in the areas of: solar collector behaviour and testing on a solar simulator; data acquisition and processing; and computing.

### **SOME EXAMPLES OF LOW-COST RESEARCH**

#### **Small-scale solar collector and simulator**

The solar simulator is used to determine the parameters of a solar collector or to obtain qualitative answers regarding test procedures, control strategy, etc. The analytical equations which describe the temperature history of the solar collector and tank indicate that the energy gain of a system, per unit collector area, is independent of the size of the system. Therefore, where the test is not to determine the parameters of an actual system the collector, hence the simulator, may be reduced by a factor of at least 10, resulting in the reduction of equipment costs by a factor of about 100. Furthermore, a special laboratory would not be required.

The small-scale solar collector system described by Munroe (1982) consists of a square copper plate  $0.09 \text{ m}^2$  in area and about 0.8 mm thick, to which was soldered as heat exchanger a serpentine pattern of thin-walled copper tubing of internal diameter 0.32 cm. The plate was painted matt-black on the heat exchanger side and housed in a shallow wooden box 33 x 33 x 3.8 cm. The glazing on the front of the collector consisted of clear perspex 0.16 cm thick and the insulation on the back 1.0 cm thick sealed polystyrene foam.

The storage tank consisted of a 4-litre capacity plastic container, which was insulated by placing it in a larger cardboard box and filling in the spaces with styrafoam chips. A further length of thin-walled copper tubing, wound into a

helix, served as a heat exchanger in the tank. A small electrically driven pump (of the type used by model aeroplane enthusiasts to pump fuel) was used to pump water in a closed loop between the heat exchangers in the collector and tank. Clear plastic tubing was used to connect the pump and heat exchangers in the loop.

Thermocouples inserted into the flow monitored the temperature of water entering and leaving the collector. Three further thermocouples monitored the temperatures at the top and bottom of the storage tank and the ambient temperature. The volume flow rate of water through the collector was measured using a small digital flow rate meter of the type marketed for measuring fuel consumption rates in cars. The output of the flow rate meter was a train of pulses with frequency proportional to flow rate.

The solar simulator consisted of a single, high intensity lamp (Thorn OM1000, CSI, 1000 watts). This provided a uniform intensity of about  $967 \text{ w/m}^2$  at a distance of about 1.5m away. Table 1 shows a breakdown of costs for the small-scale system and simulator.

Work done using the small-scale system and briefly discussed below include:

1. Validation of an equivalent electrical circuit model of the flat-plate solar water heating system (Munroe 1980).
2. Transient testing of the flat-plate solar collector (Munroe 1983).
3. A method of determining the time constant of a flat-plate solar collector (Munroe 1981).

#### Equivalent electrical circuit model

In order to evaluate the performance of solar collectors, it is first necessary to establish the criteria of performance. These are based on the mathematical model of the collector. The best known model is that by Hottel and Whillier (1955). The model assumes zero thermal capacitance for the collector and expresses the energy output in terms of the incident radiation, the difference in temperature between the collector and the ambient air, and the collector heat loss coefficient.

The basic model of Hottel and Whillier was extended by Close (1967) to include a single thermal capacitance for the collector, referenced to the mean temperature of the collector plate. A transient model for the collector by Munroe (1981) assumes a single thermal capacitance for the collector, referenced to the mean temperature of the collector liquid. The transient energy balance equation for the collector may then be expressed as

$$q_u = \dot{m}C_p(T_o - T_i) = I\alpha\tau - U_1(T_1 - T_a) - C_1 dT_1/dt \quad (1)$$

The energy balance of the storage tank on a unit collector area basis will be

$$\dot{m}C_p(T_o - T_i) = U_2(T_2 - T_r) + C_2 dT_2/dt + U_L(T_2 - T_L) \quad (2)$$

If an artificial heat transfer coefficient  $U_3$  is introduced, defined as the mean heat transfer coefficient between the collector and storage tank, such that

$$\dot{m}C_p(T_o - T_i) = U_3(T_1 - T_2) \quad (3)$$

substituting (3) in (1) and (2) and re-arranging in matrix form and taking Laplace transforms, gives

$$\begin{bmatrix} U_1 + U_2 + sC_1 & & -U_3 \\ & & \\ -U_3 & & U_2 + U_3 + U_L \end{bmatrix} \begin{bmatrix} T_1(s) \\ \\ T_2(s) \end{bmatrix} = \begin{bmatrix} I(s)\alpha\tau + U_1T_a + C_1Y_1(o) \\ \\ U_2T_R + U_L T_L + C_2T_2(o) \end{bmatrix} \quad (4)$$

A solution to equation (4) for the special case where I is a constant or step function, as obtains on a solar simulator can be expressed as

$$T_1 = A_0 + A_1 \exp(-\delta t) + A_2 \exp(-\gamma t) \quad (5)$$

$$T_2 = B_0 + B_1 \exp(-\delta t) + B_2 \exp(-\gamma t)$$

where  $A_0, A_1, A_2, B_0, B_1, B_2, \delta$  and  $\gamma$  are constants. One advantage of equation (4) is that it can be used to derive an equivalent electrical circuit for the system by inspection.

An equivalent electrical circuit for the typical closed loop, forced circulation, flat-plate solar water heating system is shown in Figure 1. A differential temperature controller has been added for completeness. In the equivalent circuit, voltage is analogous to temperature and current is analogous to heat flow. System simulation is reduced to determining the response of the circuit to any chosen time-dependent current input.

### Transient collector test

A transient test for solar collectors requires a transient model for the collector and equation (1) is used for that purpose. The transient efficiency equation is given by

$$\begin{aligned} \eta_1 &= \alpha\tau - \{U_1(T_1 - T_a) + C_1 dT_1/dt\} / I \\ &= \alpha\tau - U_1 \{ (T_1 - T_a) + kdT_1/dt \} / I \end{aligned} \quad (7)$$

where  $k = U_1/C_1$

The graph of  $\eta_1$  vs  $\{(T_1 - T_a) + kdT_1/dt\} / I$  is a straight line similar to the steady-state collector line, with intercept  $\alpha\tau$  on the  $\eta_1$  axis and slope  $(-U_1)$ . To use equation (7) as a basis for transient tests, it is necessary to determine the value of  $k$ , the ratio of heat loss coefficient to thermal capacity. This may be obtained from a cooling test. If the collector cools from an initial temperature  $T_1(i)$  to a final value  $T_1(f)$  in time  $t$  (with the circulation pump turned off), then from Newton's law of cooling

$$\{T_1(f) - T_a\} = \{T_1(i) - T_a\} \exp(-kt) \quad (8)$$

which may be re-arranged to give

$$\ln \left\{ (T_1(t) - T_a) / (T_1(i) - T_a) \right\} = \ln(\Delta T / \Delta T_0) = -kt \quad (9)$$

A transient test was carried out on the small test collector, connected up to the storage tank in the conventional configuration used for water heating. The result of the test indicates that the system is linear and the graph of  $\ln(\Delta T / \Delta T_0)$  vs.  $t$  is a straight line with slope  $k$ . This value of  $k$  is substituted in equation (7) and the graph of collector efficiency  $\eta_1$  vs.  $\left\{ (T_1 - T_a) + kdT_1/dt \right\}$  is a straight line with intercept  $\alpha\tau$  on the  $\eta_1$  axis and slope  $(-U_1)$ .

#### Collector time constant

Equations (5) and (6) indicate that the time-dependent behaviour of the collector and storage tank is determined by two time constants,  $1/\delta$  and  $1/\delta'$ . The time constant of the collector is  $1/\delta'$ , where  $\delta'$  is a function of the parameters not of the collector only, but all the other parameters of the flat-plate solar water heating system. This dynamic collector time constant can be shown to influence only the very short-term ( $\approx 3$  minutes) behaviour of the collector. The transient behaviour of the collector, however, is dominated by the dynamic time constant of the system,  $1/\delta$ , which is of the order of several hours.

The dynamic time constant of the collector is directly proportional to the thermal capacity of the collector, but further simulation studies indicate that collector capacitance has very little effect on the daily or long-term performance of the solar water heating system.

#### Computing facilities

Most computing centres have mainframe computers with an extensive library of subroutines in Fortran which are readily accessible to users and this can provide formidable support in any research project. In the case of some developing countries, computing facilities may be very limited or entirely absent.

For those researchers who do not mind learning another computer language, ie basic, and are willing to develop their own programs in basic, then there exists a range of relatively inexpensive "home" computers which can provide some research support.

Two low-cost microcomputers which can be discussed from first hand experience are the Sinclair ZX81 and the Sinclair ZX Spectrum. The ZX81 is at the lower end of the computer market and a machine with 16 kilobytes (16k) of memory sells for about £70. A machine with 64k of memory, the maximum possible for an 8-bit computer, sells for about £95. Program storage is by ordinary cassette recorder, although special computer grade cassettes are available. Suitable cassette recorders are available at about £25-£30.

If printout of results is required, then the ZX81 can be interfaced to most of the commercially available printers. The printer currently available for the ZX81 at the lowest possible cost, called the Alphacon 32, sells for about £70. A small computing system incorporating many of the mathematical functions of larger computers and with storage and printout can be assembled at a cost of less than £200. An ordinary UHF television set is required to monitor the input and output of the computer. With this included, the total cost is about £250.

The ZX81 is however, not without its drawbacks which include:

1. very slow compared with the mainframes; computing times are measured in minutes, rather than seconds
2. not very many off-the-shelf programs are available for scientific computing; program must be developed by the user
3. double precision not available
4. high resolution graphics not available; with the exception of bar charts, good quality graphs cannot be drawn on the monitor
5. poor keyboard.

Some of the drawbacks of the ZX81 may be overcome by using a ZX Spectrum. The 16k machine costs about £90 and the 48k machine costs £130. Mass storage using floppy discs are available from about £240 for 200k of storage to about £280 for 800k. The Spectrum has its own inexpensive mass storage unit - the microdrive which starts at about £150 for 100k of storage, but this may not be suitable in all cases, since the storage unit may be damaged if turned on with the disc in position. The computer can also be connected to a wide range of printers. A 16k system with microdrive and Alphacom printer would thus cost about £310. The Spectrum offers very good high resolution graphics and has the advantage over the ZX81 that it can store the results of a program without having to store the entire program - a worthwhile feature when large volumes of data are to be stored. The Spectrum is still much slower than the mainframe computer and does not offer the double precision facility. An additional plus for the above microcomputers is that there are several magazines devoted exclusively to them which give good subroutines, hints on programming, etc.

The list of suitable microcomputers has of course not been exhausted and has been confined so far to the lower end of the computer market. One of the more popular up-market machines is the Apple II, with prices for a 48k machine with disc drive and printer starting at more than £1000. Where research funding is not a serious constraint, this category of machine may be considered, since there is a wider range of off-the-shelf computer programs available and the machine can be programmed in Fortran and Pascal, as well as in Basic.

All the computations, simulations, analysis of collector test results, etc by the author which have been referenced in this paper were carried out on one or another of the three above-mentioned microcomputers. In addition, the author has served as convener of a subcommittee which drew up the initial specifications for a microcomputing centre at the Federal University of Technology, Owerri, Nigeria. The centre, consisting of a network of eight Apple II microcomputers, is presently used in teaching a second year computer course in Basic and Fortran at the University. This facility, intended to serve until a mainframe computer is acquired, is likely to be expanded to include more microcomputers in the network.

#### **Data acquisition and processing**

Data acquisition and processing is yet another area in which reasonably good equipment can be acquired at relatively low cost. If a small number of measurements are to be taken, eg a set of temperatures every ten seconds for a period of about one hour, then the equipment required is relatively simple and much of it available off-the-shelf. For this type of measurement, the author

uses a ZX81 with an eight input analog-to-digital (A/D) converter. The A/D converter presently in use was purchased from Thurnall Electronics, Manchester, at about £50.

Where a large number of measurements are to be taken over an extended period of time the above system is not adequate, since additional equipment would be required to control the cassette recorder, the only presently available mass storage unit for the ZX81. The simple system would thus not be suitable for say a data management system for solar or wind energy. The ZX Spectrum is more suited to this purpose, since it can directly control a mass-storage device, such as the ZX microdrive, a disc drive or one of the several high-speed cassette drives. An A/D converter is required for the Spectrum and though this is likely to be available off-the-shelf, the author is currently assembling one. The final cost of this item is not included here, but will be reported at a later date. In fact, a complete data management system, incorporating data acquisition, analysis, reduction and storage is presently under construction. The system is being built around the Spectrum microcomputer and when completed, would be used to monitor solar and wind energy parameters, it is described in more detail in the following paper.

### CONCLUSIONS

This paper has attempted to show that some research, though limited in scope, can still be carried out on a small research budget. It also demonstrates that computing facilities need not always be in the form of a large, mainframe computer. The new range of "home" computers, though small and slow by comparison, can still provide adequate facilities at reasonable cost.

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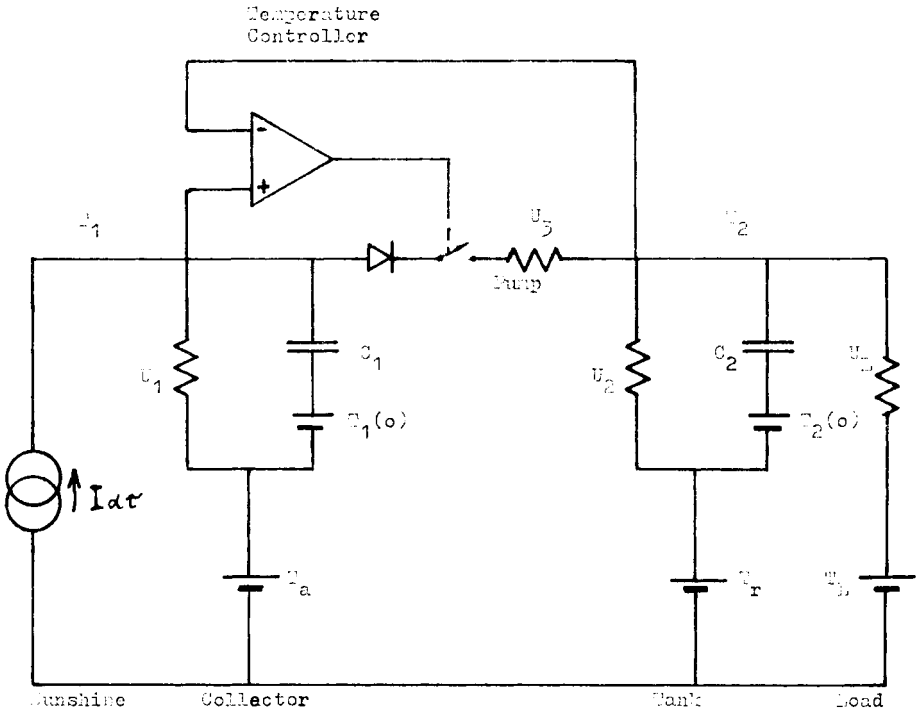
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**TABLE 1: Estimated cost of small-scale collector system and simulator**

<b>Item</b>	<b>Estimated Cost (£)</b>
Solarimeter	200
Simulator (Thorn OM1000, CSI Lamp, 1000 W)	250
Circulation pump	6
Flow rate meter	25
Solar collector	15
Miscellaneous (clean plastic tubing, plastic tank, insulation etc.)	<u>5</u>
<b>Total</b>	<b><u>511</u></b>



**FIGURE 1.**  
An electrical equivalent circuit of the flat-plate solar water heating system.

## **SOLAR WATER DISTILLATION PLANT**

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### **ABSTRACT**

The paper describes the development of an effective and economical solar water distillation plant to produce, in commercial quality, distilled water of high purity as is required by pharmaceutical, chemical, food industries, etc. The plate is currently undergoing a series of performance tests. Initial results show that the improved unit can produce larger quantities (up to 30 litres per day) of high quality distilled water. The process can also be adapted to supply potable water to rural areas where the water available is not suitable for drinking.

### **INTRODUCTION**

The objective of this project is the development of a small scale solar distillation plant to produce economically pure water of the high quality required for different purposes in various industries such as pharmaceutical, chemistry and food industries and for motor batteries, laboratories and hospitals. Solar water distillation can be very economical if well designed especially in countries such as Nigeria with abundant sunshine all the year round.

### **HISTORICAL BACKGROUND**

In 1982 two experimental solar stills of galvanised mild steel body and glass pane covers were constructed at Kaduna Polytechnic, Kaduna. Each unit had a tray area of  $2.1\text{m}^2$  for heating water by solar radiation and produced on average 8.6 litres of distilled water per day or about 4.1 litres per  $\text{m}^2$ . The production gradually declined to 2.5 litres per  $\text{m}^2$  per day in April 1984.

In laboratory analysis of samples of distilled water collected in January 1982, the pH was 7.0, electrical conductivity was 17 micro mhos and traces of calcium, magnesium and sodium were within international standards. The maximum temperature of water in the tray reached  $68^\circ\text{C}$  with an ambient temperature of  $39^\circ\text{C}$  and corresponding output of 12 litres on 6th April 1982. During the two years operation, the units were overhauled twice and during the second overhaul it was discovered that one of the units had corroded badly with many pit holes in the base plate.

Initially the units were not lagged and hence lost a lot of heat energy to the surrounding atmosphere. Scales forming on the base of the tray covered the black coating and considerably reduced the thermal efficiency and the daily production.

### **AN IMPROVED UNIT**

Based on the experience described above it was decided to design an entirely new solar water distillation process plant (Jimoh and Gupta 1984). This process incorporates pre-treatment of the water by sedimentation and filtration, preheating of the filtered water using a solar collector, and multi-stage distillation by a serial arrangement of stills (Figure 1).

The still is 1.75m x 1.22m and made of stainless steel. It has a copper sheet base, a glass pane cover and is insulated with 50mm thick polyurathane foam enclosed in plastic coated steel sheets. The inclination of the glass pane is 12° to the East-West horizontal plane to allow condensed droplets to run along the glass pane to the V-shaped channels leading to the plastic tubes carrying the distillate to the storage plastic container.

Water is supplied automatically through a float valve to the filter tank fitted with four filter elements mounted directly on the supply tank. The filter water is supplied through a plastic hose pipe and a level control float valve to the still. Preheating of the solar collector was rejected as this had very little effect especially with the introduction of a water level control float valve which only released the supply water as droplets into the still.

The entire process functions automatically and requires only one attendant to dust the glass panes daily and to collect the distillate.

### OBSERVATIONS

Performance tests are still being carried out on the new installation which went into operation in December 1984. The following preliminary observations have been made:

1. The average daily quantity of distilled water produced for the month of December 1984 was about 30 litres at average ambient temperature of 30°C making about 14.3 litres per m<sup>2</sup>.
2. The maximum water temperature of 68°C was recorded on 22nd February 1985 with ambient temperature of 38°C.
3. The first analysis of the distillate, carried out on 6th December 1984 by the soil laboratory of the Department of Irrigation/Agriculture Mechanisation gave the following results:

pH	=	6.8
EC x 10 <sup>6</sup>	=	4.35 micro ohm/cm at 25°C
CO <sub>3</sub>	=	None
HCO <sub>3</sub>	=	0.3 meg/l
CA <sup>++</sup>	=	2.4 ppm
MG <sup>++</sup>	=	None
Cl <sup>-</sup>	=	None
Ma <sup>++</sup>	=	None
K <sup>+</sup>	=	None

Water colourless and odourless.

The water is being collected temporarily in plastic containers and the permanent distillate tank is to be installed later.

### CONCLUSION

The 400% increase in average daily production from 4.5 litres per m<sup>2</sup> to about 143 litres per m<sup>2</sup> in the improved solar still is still being investigated, but can be attributed to:

1. the initial pretreatment of the supply reducing the sediment considerably;
2. the automatic level control float valve maintaining a constant water level (presently about 25mm high in the tray);
3. the use of a copper tray which increases the rate of energy absorbed by the water;
4. the insulation of polyurathane foam which prevents heat loss to the surrounding atmosphere.

Further experiments are being planned.

### **ACKNOWLEDGEMENTS**

This solar water distillation research project is financed by the Research and Evaluation Committee of Kaduna Polytechnic. The author is particularly grateful to the Rector Engr H A Tukur for his personal interest in and support for the project and then to all colleagues of Kaduna Polytechnic who have assisted in one way or the other to make the project successful.

My thanks specially to Mr H C Gupta for going through the scripts.

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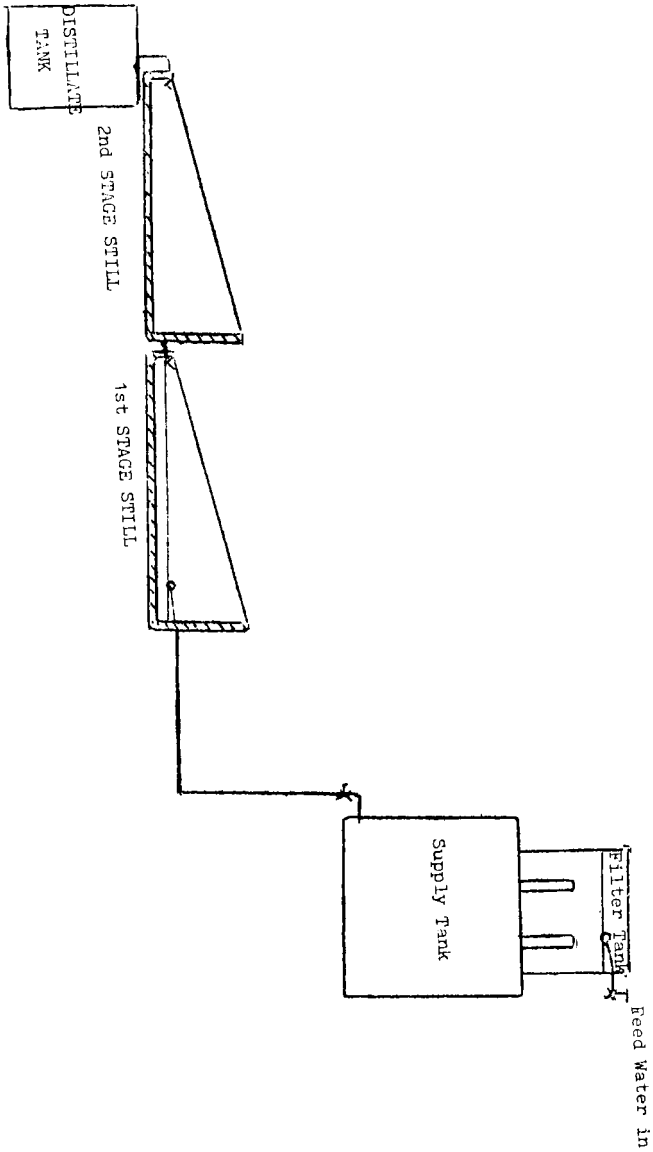
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FIGURE 1: Solar water distillation process diagram



## **PERFORMANCE OF FLAT PLATE COLLECTORS IN RELATION TO CORROSION PROBLEMS**

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### **ABSTRACT**

The performance of four types of plate collectors is discussed in terms both of instantaneous efficiency and the overall efficiency of the complete solar energy water heating system. The influence of corrosion on the durability and performance of these collectors is discussed.

### **INTRODUCTION**

The Whillier and Hottel equation lays out a model for analysing the performance of flat plate solar collectors. However, results of instantaneous performance tests do not necessarily relate closely to the performance of an installed system.

To gain a realistic view of the relative performance of solar water heaters therefore requires consideration not only of the efficiency of the solar collector in capturing solar energy, but also the efficiency of the whole system in terms of heating water under normal operational conditions. The life span of the system is also an essential criteria for selecting a solar water heating system. Again this can only be assessed through operating the system for an extended period of time.

As part of a long-term solar energy research programme (Zingano 1983), the performance and durability of various plate collectors and solar water heaters was tested. All collectors and heating systems were available and constructed in Malawi. Instantaneous collector performance tests, details of which are not provided here, and performance of the system under typical sky conditions are discussed.

### **TYPES OF FLAT PLATE COLLECTORS**

Four collectors were tested which fall into three categories of solar collectors:

**Type A.** Sandwich Type: This collector was constructed out of two plates of 0.5mm galvanised steel and separated by 4mm wide silicone rubber blocks to form the water channel. The plates were coated with a black acrylic paint and seamed on all edges. The cover was 3mm crown glass laid in sections of 230 x 225mm and 8mm above the absorber surface.

**Type B.** Grid Type: There were two versions of this type of collector:

Type B1: This collector was constructed out of 13mm galvanised pipes as the grid with a 19mm diameter manifold at both top and bottom. The single risers of the grid were half wrapped in 0.5mm plates of galvanised steel painted as in type A. The cover was 4mm glass fixed at 100mm above the absorber plate. Riser spacing was 100mm.

Type B2: This collector was constructed as Type B1 but the grid risers were spaced at 100mm finned in 0.5mm galvanised plates measuring 150mm across. The cover was 3mm fibreglass.

**Type C.** Snake Type: This collector was similar to the grid design, but the water channel was a continuous looped copper tube 19mm in diameter strapped to a 0.5mm galvanised steel plate. The cover was 4mm glass at 75mm above the absorber surface.

### **SOLAR WATER HEATING SYSTEMS**

Five systems were tested.

**System A.** Collector type A was coupled to a storage tank with a built in ball valve and was a normal syphonic system.

**System B.** Collector type B was coupled to a similar storage tank as in A, but as a once-through system. In this arrangement the pressure of the incoming main was regulated by a pressure reducing valve. The automatic inlet regulating valve was specially developed for this purpose. It was regulated by a thermal valve which was designed to respond to radiation intensity. Thus the valve was activated at an irradiance level of  $150\text{Wm}^{-2}$ . At this intensity the water trickled through the collector and dropped into the storage tank. The minimum temperature was  $40^{\circ}\text{C}$ . The water did not recirculate and therefore was not exposed to further heat losses.

**System C.** Collector type B1 was connected to a vertical tank and the system worked in a normal syphonic circulation.

**System D.** Collector type B2 was connected to a horizontal storage tank with a side make up tank and a ball valve. This was a syphonic system.

**System E.** Collector type C was connected to storage tank but with an option of mounting the tank horizontally or vertically. Again this system was syphonic.

### **TEST SITE AND SYSTEM TEST PROCEDURE**

Collectors and systems were tested on the roof of a laboratory about 3m above the ground and facing north. The tests were carried out between April and July which are winter months in Malawi. For maximum normal solar insolation the collectors were fitted at  $14^{\circ}$  from horizontal. An eppley solarmeter was used to record the insolation and the ambient temperature was recorded at a nearby Stevenson Screen. The wind speed was monitored and throughout the tests this did not exceed  $5\text{kmh}^{-1}$ .

Systems were left in operation for a whole day without drawing off any water. The temperature of water in the mains was recorded before sunrise each day. At that time the storage tanks were checked to make sure that they were full of water.

After sunset when exit temperature is the same or lower than the inlet temperature ( $T_{fe} T_{fi}$ ) all the water in the tank was drawn off in 14.5 litre buckets. This unit was chosen because it is the volume of a common vessel used for hot baths in Malawi.

An extensive statistical survey established that what is commonly termed a "hot bath" is only 40°C. The temperature of each bucket was carefully recorded until the storage tank was completely empty.

On each day the sky conditions were recorded and the cloud cover was expressed as a fraction of eight hours. Thus 0/8 was a clear day and 8/8 represented an overcast day.

## RESULTS

### Instantaneous efficiency test

The results of the instantaneous performance test are shown in Figure 1. The X and Y intercepts of the graphs and the extracted FU values are given in Table 1.

### Systems efficiency test

By extending the Whillier and Hottel equation to cover the collector, transmission pipes, and the storage tank, the final equation would be as follows (explanations of symbols are given in the appendix to this paper).

$$\eta_s = \frac{Q_u}{IA_c} = F(UR) \left\{ \left[ F U_c \frac{(T_{mc} - T_a)}{I} \right] + \left[ \frac{U_t A_t}{A_c} \frac{T_{mt} - T_a}{I} \right] + \left[ \frac{U_p A_p}{A_p} \frac{T_{mp} - T_a}{I} \right] \right\} \quad (1)$$

The useful energy obtained by the system was integrated as follows:

$$Q_{ut} = C_p \sum_{i=1}^N M_i (T_i - T_{supply}) \quad (2)$$

The average days efficiency can then be obtained from the following equation:

$$\eta_s = \frac{C_p \sum_{i=1}^N M_i (T_i - T_{supply})}{I_{gt} A_c} \quad (3)$$

The results of this test are shown on Table 2.

### Relation of cloud cover to system efficiency

The results of the systems test were plotted against the cloud cover record (Figure 2). Efficiency declined as the cloud cover increased.

### Rating of collector systems based on the "hot bath" (40°C) temperature criteria

The minimum temperature of hot water required by a user was taken to be 40°C. As a further assessment of efficiency, the amount of water above 40°C obtained by each system was calculated. Table 3 compares the five systems in terms of the volume of water produced over 6 days by each system at or above 40°C, and expressed as a percentage of the hot water storage tank.

This merely provides a guideline to the user since the systems were being sold in these sizes. A purely scientific comparison would have taken into account the collector aperture to storage tank ratios, and then the storage tank surface area to volume ratios in order to normalise the comparison.

## **DISCUSSION**

According to the instantaneous efficiency test alone the most efficient type of collector is the sandwich one while the snake type is the least. The former has a very short heat path, ie absorber to water while the latter has a somewhat longer path, ie absorber to pipe and then to water.

However, the sandwich type collector has the highest heat loss factor. This may be related to the design and the width of the air gap between the absorber surface and the transparent cover. In this type of collector the thermal insulation above the collector is therefore not as good as in the others.

Based on performance tests of the overall system, system B is the best while system D is the worst of the five systems. Although collector type B<sub>2</sub> performed better than collector type C and B<sub>1</sub> in the instantaneous efficiency test this did not hold true in performance testing of the system under normal operation.

### **Flat plate collectors and corrosion**

The performance of solar collectors in terms of efficiency is only one parameter of the economic effectiveness of the device. The other parameter is the life of the device once it has been installed. Basson (1980) has outlined materials for construction of these devices which combine good performance and long life at an effective cost.

Corrosion is mainly caused by constituents present or absent in the water. Campbell and Turner (1983) have evaluated and investigated the main causes of corrosion in metals in general. Most of their findings agree with the experience of the author with installed solar collectors in Malawi. Generally, corrosion is more pronounced in the absence of furring of the water channels. The calcite deposition protects the metal from corrosion.

Dissolved salts in water form "nodules" scales at high electricity current densities but "egg shell" scales in low electricity current. Modular scales formed of temperatures above 60°C differ from those formed at room temperatures, and have more circular crystals. The principal salts in the scales are from sulphates and carbonates of sodium and calcium.

In the absence of electrolytic corrosion the presence of chlorides, chlorine, excessive dissolved oxygen and in general the elements which become cathodic stimulants lead to corrosion. In two cases the author has analysed solar collector failures and it has been found to be related to the presence of these agents and a function of the source of the water.

Solar collector corrosion is more pronounced if the source of the water is underground. This phenomenon has been attributed to the absence of a "prohibitor" (Campbell and Turner 1983). This prohibitor is now believed to be colloidal and the heavier the molecule the better is its prohibiting influence. Thus surface water is a likely medium to contain this prohibitor. This has been the observation in Malawi too. Solar collector installations drawing water from rivers have lasted longer than those drawing water from lakes and the latter in turn have lasted longer than those drawing water from boreholes. An analysis of the water has only indicated increased dissolved salts in the order of river water, lake water and ground water.

"Egg shell" scale formation is to be preferred to "nodular" scale formation. The former spreads across the metal surface better than the latter and therefore protects the metal. On the other hand the latter narrows the water channel faster and leaves pits where the metal is still exposed to the corrosive agents.

The basic construction of the collector has some effects on furring up of the water channels. Thus although the sandwich solar collectors are more efficient the scale formation narrows the passage faster and increases both the thermal and hydrolic resistances.

### **CONCLUSION**

Generally the intrinsic efficiency of a sandwich solar collector is higher than that of a grid or snake type. However this advantage can be lost if the system installation is not the right one. In all types of solar system installations the efficiency drops inversely proportional to increased cloud cover.

To ensure an extended life of a collector it is advisable to treat all water to have a composition close to that of river water in terms of organic matter content. It is better to have wide water channels in collectors of the sandwich type and this is where the grid type has an advantage.

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**NOMENCLATURE**

$A_c$	=	aperture of collector
$A_p, A_t$	=	surface area of transmission pipes and storage tank respectively
$C_p$	=	specific heat of water
$F$	=	drain factor
$I$	=	intensity of irradiance
$I_{gt}$	=	total global radiation on a horizontal surface
$Q_u$	=	useful heat gained
$Q_{ut}$	=	total useful heat gained
$T_a$	=	ambient temperature
$T_i$	=	initial temperature
$T_{fw}, T_{fi}$	=	exit and inlet temperatures respectively
$T_m$	=	average of exit and inlet temperatures
$T_{mc}, T_{mt}, T_{mp}$	=	mean water temperature in collector, storage tank and transmission pipes
$T_{supply}$	=	temperature of main water
$U_c, U_p, U_t$	=	heat loss factor for collection, transmission pipes and storage tank
$\tau(\omega)$	=	product of absorption and transmission factors
$\eta_s$	=	system efficiency
$\bar{\eta}_s$	=	average system efficiency
$\eta_c$	=	collector efficiency

**TABLE 1: Performance characteristics of four flat plate collectors and their apertures**

Collector Type	Zero radiation efficiency ( $F ( ) \times 100$ )	Heat loss factor $FU (Wm^{-2}C^{-1})$	Zero efficiency temperature ( $^{\circ}C$ )	Aperture ( $m^2$ )
Type A	90	10	113.3	1.86
Type B <sub>1</sub>	54.3	5.3	122.0	0.86
Type B <sub>2</sub>	57.3	9.9	79.3	1.53
Type C	55.7	9.9	80.3	1.31

**TABLE 2: Systems performance for six days**

Test No.	Total irradiance $I_{gt} (MJ/M^{-2})$	System efficiency					Cloud condition
		A	B	C	D	E	
1	17.58	21	26	1.9	2.3	8.6	5/8
2	13.06	48	57	19	6.7	25	3/8
3	17.37	39	39	20	18	31	2 5/8
4	15.66	56	53	25	24	40	1/8
5	16.74	48.9	45	19	23	35	3/8

**TABLE 3: Volumes of water at or above 40°C collected by systems and the volume of the hot water expressed as a volume of the storage tank**

System No.	Volumes of water at or above 40°C and percentage of tank nominal capacity						Total radiation Mj/m <sup>2</sup>
	A Litres %	B Litres %	C Litres %	D Litres %	E Litres %		
08.06.82	78 46	62 36	26 58	0 0	0 0	0 0	17.6
11.06.82	130 76	142 84	29 64	0 0	0 0	0 0	13.1
17.06.82	99 58	154 91	0 0	73 63	58 32		19.5
24.06.82	116 68	132 78	29 64	0 0	0 0	0 0	17.4
25.06.82	150 88	160 94	44 98	0 0	44 24		15.7
26.06.82	147 86	163 96	29 64	0 0	29 16		16.7
<b>Total</b>	<b>720</b>	<b>822</b>	<b>103</b>	<b>73</b>	<b>131</b>		
<b>Rating</b>	<b>2</b>	<b>1</b>	<b>4</b>	<b>5</b>	<b>3</b>		

FIGURE 1: Graph of efficiency for the four collectors

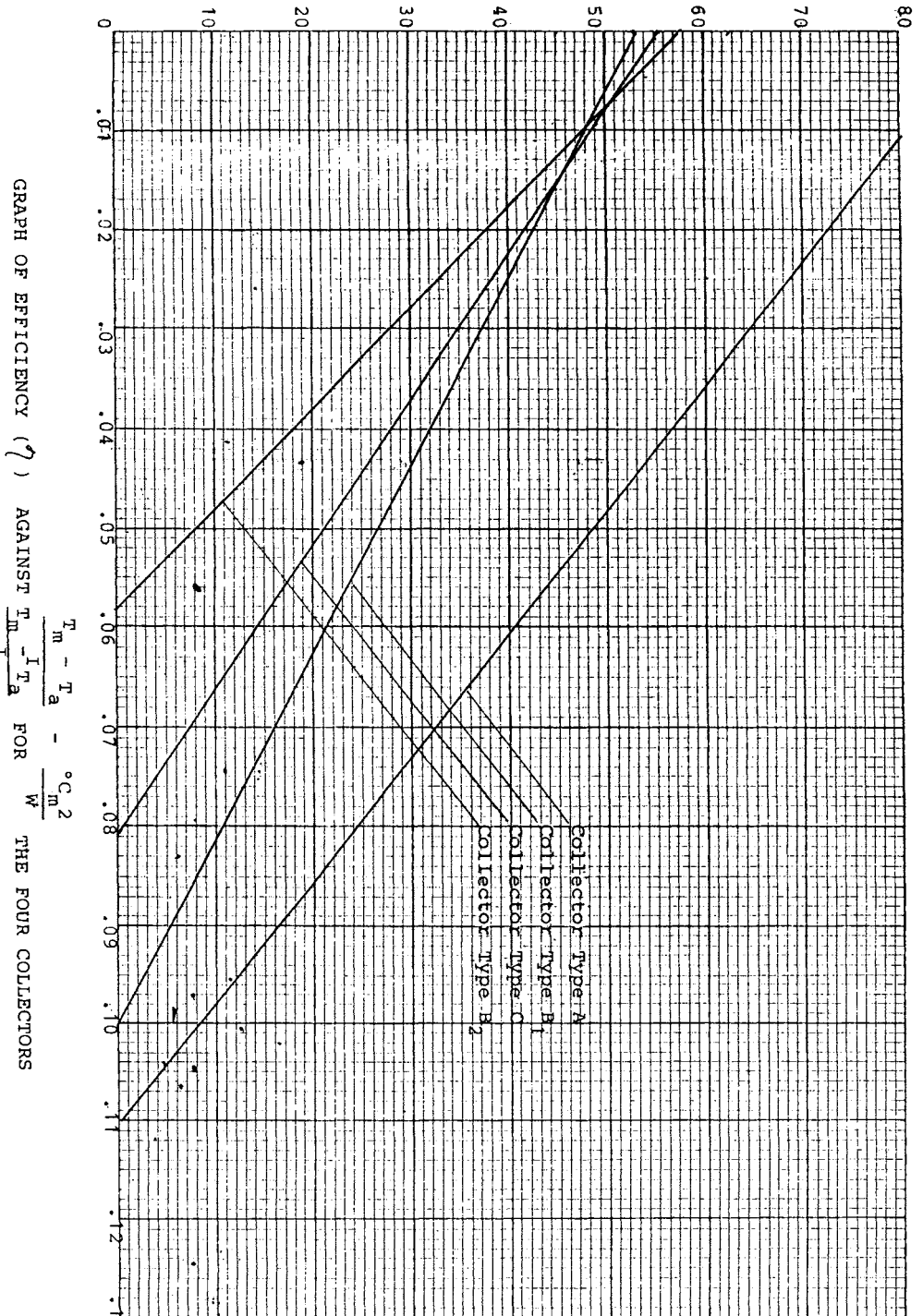
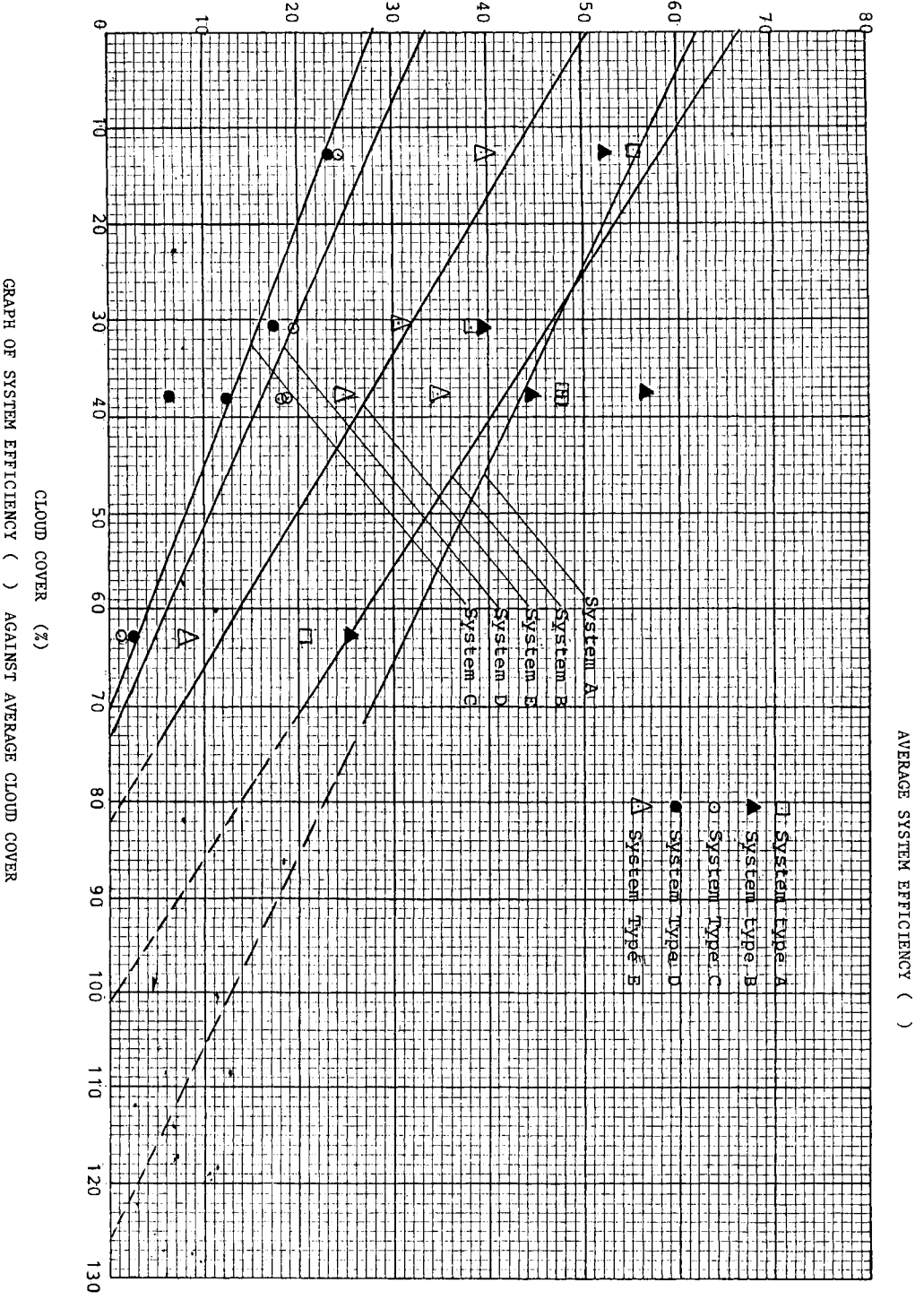


FIGURE 2: Graph of system efficiency against average cloud cover



## SOLAR WATER HEATER DEVELOPMENT IN NIGERIA

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### ABSTRACT

Electricity supply is limited and its cost is also increasing steadily. Solar energy is abundant and it may be economically utilised as a supplement to electric power, if appliances such as solar water heaters, air heaters, dryers, air conditioners etc are made available at low cost. So it is important to develop methods and technology for the utilisation of solar energy. A solar water heater has been designed and fabricated for domestic and industrial uses which can be commercialised. While carrying out this project we also aimed at developing awareness and skills in using locally available materials in efficient and economical ways, thus becoming independent of imports.

The typical solar water heater consists of a flat plate solar collector, an insulated hot water storage tank and the piping system. A prototype, 1.1m<sup>2</sup> flat plate solar collector was fabricated from locally available materials (Y A Jimoh 1983). It was tested in a thermosiphon water heating system connected to a 62 litres insulated storage tank.

Performance tests were carried out over a period of one year. The results were quite satisfactory with the net absorbed power being, on average, about 250W per square metre collector area (considering a day of 8 hours from 8.00 am to 16.00 pm). The range varies from 0 to 600W per m<sup>2</sup> depending on the intensity of solar radiation.

The cost of the complete solar water unit at the time of construction (January 1983) was 500 Naira. At present, the cost is estimated to be about 1,000 Naira. Further work to increase the efficiency of the solar water heater involved improvement to both the collector and the insulated storage tank. Progress will be reported in due time.

### INTRODUCTION

Researchers at Kaduna Polytechnic, Kaduna, Nigeria have been designing and developing an appropriate and efficient solar collector using locally available materials and skills as far as possible. The solar collector will be used to supply the newly constructed student canteen with all its hot water. The initial capital investment is expected to be offset by the savings made in the running cost.

This paper describes the design and evaluation of the performance of a prototype collector.

### SOLAR COLLECTOR DESIGN

Solar collectors exist in various forms and types but for our solar water heater project flat plate collectors were selected because of their simple geometrical form, which makes for simple construction from locally available materials. They also have comparatively good performance.

The main components of a flat plate solar collector are the absorber, the heat exchanger, insulation, and the frame and cover. These are discussed in the following sections.

### **The absorber-heat exchanger**

Because of cost constraints and the level of technology in Nigeria, the absorber-heat exchanger was fabricated from galvanised mild steel plate and copper pipes. Aluminium sheets and pipes were considered, but aluminium pipes are not available locally.

The final selection of a combination of mild steel plating and copper tubing has sufficient thermal efficiency and is an optimum economic solution. Efficiency can be further improved by double glazing, honey combing, etc.

The absorber-heat exchanger was constructed using 12.5mm copper riser pipes spaced at 125mm. Riser pipes were joined to 25mm copper headers. A 2mm thick galvanised mild steel plate was cut to fit the spaces between the copper pipe and headers. The whole unit was coated in matt black paint.

### **The insulation**

Initially, a combination of chipboard and glass fibre was used as insulation for the collector and the storage tank. It has now been replaced with polyurathane foam which has a very low thermal conductivity ( $0.026 \text{ W/m}^\circ\text{k}$ ) and is abundantly available locally.

### **The frame**

The collector is enclosed by a galvanised mild steel frame, lagged for long life and durability. The frame is 1230mm by 925mm and includes a glass cover selected for durability against adverse weather conditions, good transmittance, low absorbance, dimensional stability and availability in the local market.

## **WATER STORAGE TANK AND PIPING**

The hot water storage tank used in the tests of performance of the solar water heater was a 62 litre rectangular mild steel tank lagged with 10mm thick glass fibre and enclosed in a chipboard box. This tank remained above  $40^\circ\text{C}$  overnight. This is now to be replaced with a 100 litre tank which is double walled with polyurathane foam lagging.

### **COST**

The complete solar water heater installation comprising  $1.1\text{m}^2$  collector, 62 litres hot water tank, piping, frame fitting and wooden supports cost N500 in 1982. The cost can still be considerably reduced if units are mass produced.

### **PERFORMANCE TEST**

During performance tests the collector was connected to a 62 litre storage tank by lagged galvanised steel pipes and fittings in an open circuit thermosiphon system. The collector frame was inclined at an angle of  $12^\circ$  to the horizontal, towards the south as Kaduna is situated at about  $12^\circ\text{N}$  latitude.

Thermometers were installed at the entry and the outlet of the collector. Provision was also made for measuring the temperature of water in the tank. Readings taken included: (i) ambient temperature  $T_A$  in  $^{\circ}\text{C}$ ; (ii) collector inlet temperature  $T_1$  in  $^{\circ}\text{C}$ ; (iii) collector outlet temperature  $T_2$  in  $^{\circ}\text{C}$ ; (iv) the temperature of the water in storage tank  $T_3$  in  $^{\circ}\text{C}$  were recorded daily on hourly basis from 8 am to 3 pm.

Table 1 shows typical daily temperature recordings from 8.00 to 18.00 hours and the calculated power output  $P$  in watts of the collector.

### **OBSERVATIONS**

With the full capacity of 65 litres of water in the thermosiphon system, the collector outlet temperature was  $55^{\circ}\text{C}$ , collector inlet temperature  $49^{\circ}\text{C}$  and water temperature in the storage tank  $50^{\circ}\text{C}$  on a cloudy, windy day. The highest water temperature was achieved in the storage tank,  $78^{\circ}\text{C}$ , was recorded on April 5th 1983 at 13.00 hours on a day with an ambient temperature of  $38^{\circ}\text{C}$ .

The mean net power output of the collector determined from the heat energy gained by water when the temperature in all parts of the system is almost equal is 265W per square metre collector area. But the power output of the collector varied between 0 and 600 W per  $\text{m}^2$  during the day depending on the intensity of solar radiation.

The power output can be considerably improved for normal water heater operation where water is taken out and the same quantity is automatically added in domestic and industrial installations. A larger capacity tank will improve the thermal efficiency.

### **SUGGESTIONS FOR IMPROVEMENT**

1. The design is to be modified by eliminating the copper pipes and making a thin box with a copper absorber plate on the top and a steel plate behind a 100mm polyurathane foam lagged hot water storage tank.
2. The frame can be made of seasoned and painted wood. This would extend the life of the unit and improve the insulation of the absorber plate.
3. The use of foam as insulation will reduce cost and weight.
4. The storage tank is to be installed near to the collector to reduce head loss due to friction. Installation of a solar energy powered pump will further improve the thermal efficiency of the unit.

### **CONCLUSION**

Experience gained from this prototype has indicated that efficient solar water heaters for domestic and industrial applications in Nigeria can be successfully developed and produced at less cost than imported ones. Encouragements and incentives should be provided for the development of these types of import substitution projects.

### **ACKNOWLEDGEMENT**

My sincere thanks go to the Kaduna Polytechnic for sponsoring the project, to my colleague Mr Gupta for going through the scripts and to Messrs R Khan and A O Omolokun for the helpful discussions and suggestions.

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**TABLE 1: Typical daily temperature records and hourly power absorbed**

Total capacity of water in the system : 65 litres

Date	Time	T <sub>A</sub>	T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>	T <sub>4</sub>	Power output P-Watts
8.3.84	8.00	27	26	26	48	0	0
	9.00	29.5	41	43	48	0	0
	10.00	31.5	45	50	50	2	152
	11.00	32	49	56	56	6	456
	12.00	36	55	62	61	5	380
	13.00	38	60.5	60	57	6	456
	14.00	39	66	73	72	5	380
	15.00	39	72	76	74	1	76
	16.00	38	72	74	73	-1	-76
	17.00	36	62	69	68	-5	-380
	18.00	34	52	53	65	-3	-228

- T<sub>A</sub> = Ambient temperature
- T<sub>1</sub> = Collector inlet temperature
- T<sub>2</sub> = Collector outlet temperature
- T<sub>3</sub> = Temperature of hot water in storage tank
- T<sub>4</sub> = Hourly difference of T<sub>3</sub>

### **C. WIND POWER GENERATORS**

## **A CASE STUDY ON FIELD TESTING OF WINDPUMPS IN INDIA**

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### **ABSTRACT**

This paper describes a simple approach to the testing of appropriate technology design windpumps and some early experience in operation of a relatively simple field test. This field test includes comparative assessment under identical conditions, an impartial record of maintenance requirements, and generates performance data to predict the quantity of water likely to be lifted on gross monthly basis at different places.

### **INTRODUCTION**

There is considerable interest in designing low cost wind pumps for the irrigation of small farms. In 1976-77 a project was initiated to design a sail-type windmill of 10m diameter (later reduced to 7.5m) coupled with a rotary pump. Two prototypes were monitored in an open field at the National Aeronautical Laboratory (NAL). Performance was monitored by hourly and daily aggregate output measuring average with hub-height wind speeds.

Multivane windmills of appropriate technology type have also been developed by other institutions. Field performance data in respect of these designs were not available and extrapolated claims, calculated apparently on the basis of short term tests, seemed optimistic.

If decision makers are to make the best choice between the available technology, it is essential to substantiate claims of cost-effectiveness through appropriate and comparable tests of performance. It was therefore decided to simultaneously operate several different windpumps in the same field under identical conditions.

A number of sophisticated field tests are used in several industrialised countries for testing wind electric generators. Meel and Oldenkamp (1984) report a single example at Eindhoven in the Netherlands.

This paper describes a relatively simple approach to measuring performance which would be suitable for any developing country without external assistance.

### **A TENTATIVE METHODOLOGY FOR WINDPUMP TESTING**

1. **Emphasis on shallow wells:** As stated earlier, the field testing discussed in this paper is primarily for the use of windpumps for irrigation in small farms from shallow open wells. Therefore, this activity reflects performance measurement in the range of total head not exceeding 8 metres.
2. **Emphasis on gross performance data:** One aspect of this programme has been to put more stress on comparative gross performance of windpumps under identical conditions. It is also envisaged to generate performance data on 10 minute averages as well as analysis of wind distribution at the site recorded by means of an anemograph.

Therefore, performance at sites of different wind distribution can be extended later.

However, wind velocity distribution data are available only in 37 locations in India. Monthly mean wind speed data are available for 317 locations. Therefore, as a first approximation, gross performance over 24 hours and aggregated performance over a period of a month and longer have been used.

3. Emphasis on extended testing: Endurance testing of the prototypes is carried out in the field to determine the fall in performance, if any, over time and obtain an idea of maintenance requirements. This is essential in respect of appropriate technology designs due to lack of standardisation.
4. Measurement of rotor power coefficient: As a side study, power coefficient of the rotor was determined treating a rotodynamic pump as a calibrated load. The pump was tested in the laboratory to determine its input power requirement at different rotational speeds for selected static heads. By measuring pump speed and hub-height wind speeds under steady wind conditions of 5-10 second duration, it was possible to estimate power drawn by the pump and thereby the power coefficient of the rotor inclusive of gear trains. This was possible only in respect of the NAL sail windmill which has a rotary drive train coupled to a rotodynamic pump.

### EARLY EXPERIENCE WITH SAIL WINDMILL TESTING

#### NAL sail windmill

While the development of this windmill is not the subject of this paper, aspects which have a bearing on its field testing will be described. This windmill consists of a low-cost sail rotor of 7.5m diameter. Initially, sails were triangular in shape typical of Greek designs. After development of a novel spoiler type regulation, the plan form of blades were changed to trapezoidal since manual furling for which triangular shape is more convenient, was no longer required. This windmill is intended to operate rotary and rotodynamic pumps kept at the ground level. There is a vertical drive shaft supported at the top and the bottom of the tower (Figures 1 and 2). The housings at the top and lower end consist of mass produced bevel and hypoid gears which also provide the necessary rotor speed step-up required for the pump.

Since 1978 prototype testing of the NAL sail windmill has been carried out on a well exposed field situated in the campus. However, since prototypes have also been undergoing developmental changes, the testing has not always been continuous. A flow meter was placed in the return delivery line for taking advantage of the fact that discharge from rotary and rotodynamic pumps was not of intermittent nature. In the absence of a good source of water supply, the testing was carried out by devising a recirculatory arrangement simulating a total static head of 6-8 metres.

Almost uninterrupted flow meter data are available from at least one of the two prototypes during the last two years. Measurements were carried out once a day on water meter and cup counter anemometer. A plot of 24-hourly discharge against wind speed indicated fairly good correlation. This was confirmed in more recent tests in which the rotary vane pump was replaced by regenerative turbine

pump and prototypes had either triangular sails or rectangular sails (Figure 3). Correlation of performance with Weibull parameters is planned for the future.

#### **Determination of rotor power coefficients**

Wind speed was measured by means of an electrical cup anemometer. The speed of rotation of the pump shaft was continuously recorded by a tachogenerator. In this manner, pump speed and wind speed correlation were established by selecting only steady records of 5-10 second duration. Observations which represented conditions under which the rotor appeared to be in the process of orienting with the direction of the wind were rejected. Also peaks representing instantaneous gusts were not considered.

The measured rotational speed of the pump was interpreted in terms of power absorbed by the pump. This was possible from variable speed pump characteristics determined on a test bench in the laboratory. Care was taken to match the total static head in both laboratory and field conditions.

Figure 4 give the power coefficient of the rotor (which includes losses in gear trains and shafts). The details of the test are provided Ramesh (1985).

#### **Extended testing of components**

Four additional wind pumps were field tested using three types of sail material, namely, medium and heavy quality canvas ( $500 \text{ gm/m}^2$  and  $750 \text{ gm/m}^2$ ) and woven polypropylene. The pumps were operated for 2-3 years period. Synthetic material was only 18-24 months.

Initially the windmill was designed around a commercially available swinging-vane rotary pump (Figure 5). This pump appeared scientifically matched with a medium solidity windmill rotor since it does not load the latter until it has picked up some speed (Tewari et al 1978).

During field operations this pump showed significant amounts of wear on the tips of the vanes. This was primarily attributed to the high coefficient of friction between brass and aluminium in the presence of water. In addition, earlier prototypes did not have rotor speed regulation which resulted in increased contact pressure due to centrifugal forces.

Experiments were made with bonded rubber tips on brass vanes but these needed replacing every month. These findings suggest that this pump requires significant development for use with windmills and it was experimentally replaced by a rotodynamic pump.

Due to the absence of automatic regulation, the design wind speed and rotor speed depended largely on how timely manual furling could be effected in the event of a sudden storm. Therefore, choice of gear strength and fatigue life was somewhat arbitrary. While rotary vane pump power characteristics did not create problems for gears, the occasional high loads at pump speed beyond its rated value which is typical of centrifugal pumps results in premature gear failures. This problem was resolved by using stronger gears and the development of an automatic technique for rotor speed regulation (Tewari and Ramesh 1983).

In early gear box designs the arrangement for lubrication was not adequate in field testing. Subsequently, greater care was taken to ensure flow and retention of lubricant in bearings and at gear contacts.

### **TESTING OF OTHER WINDPUMPS**

Two multivane windpumps are being tested in identical conditions at NAL campus as shown in Figure 6.

At present water is being lifted by windpumps from shallow sumps of about 3m depth. The pump lifts water by an additional 2 to 5m depending on the design. Figure 7 shows the recirculatory arrangement through a watermeter.

While extended testing is necessary, preliminary findings suggest a significant decline in performance of these low cost appropriate technology design windpumps (Figure 8). The pump being used is not constructed from non-corrosive metal. There was no rigorous attempt to match its parts and it was a very cheap model for its size (15cm diameter, 25cm stroke, two air chambers costing 1500 Indian rupees).

### **CONCLUSIONS**

From the studies conducted it is possible to recommend that simple and inexpensive field testing of windpumps can provide very useful information for the development and evaluation of low-cost appropriate technology designs primarily intended for irrigation in small farms from shallow wells.

### **ACKNOWLEDGEMENT**

The author wishes to thank his colleagues and DNES, for sponsoring this field testing project.

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**FIGURE 1: NAL sail windmill with triangular sails**

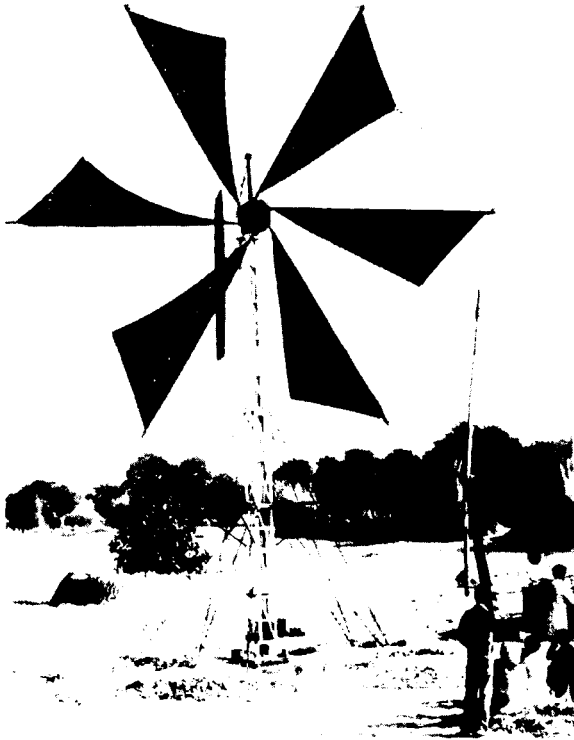


FIGURE 2: Schematic arrangement of NAL sail windmill

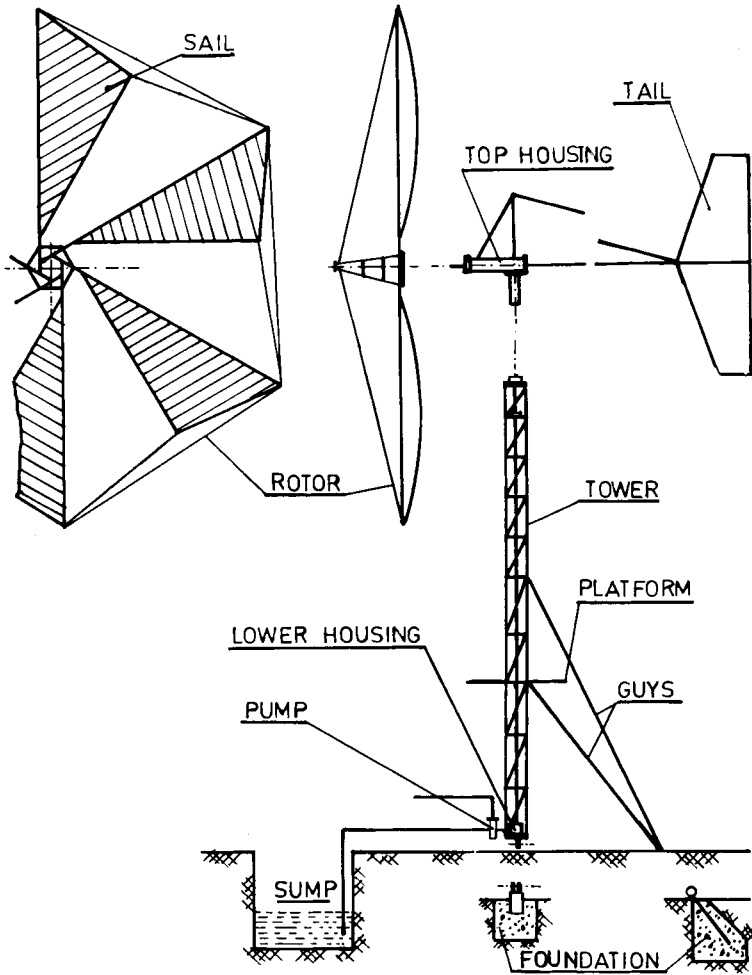


FIGURE 3: 24-hourly discharge and average wind speed correlation

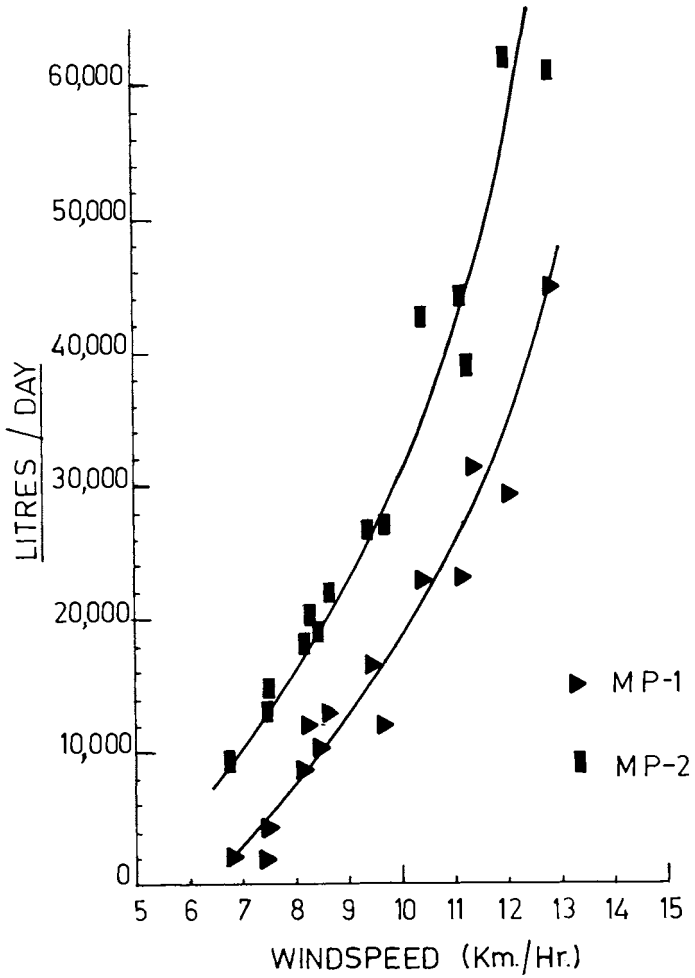


FIGURE 4: Rotor power coefficient shown against tip speed ratio

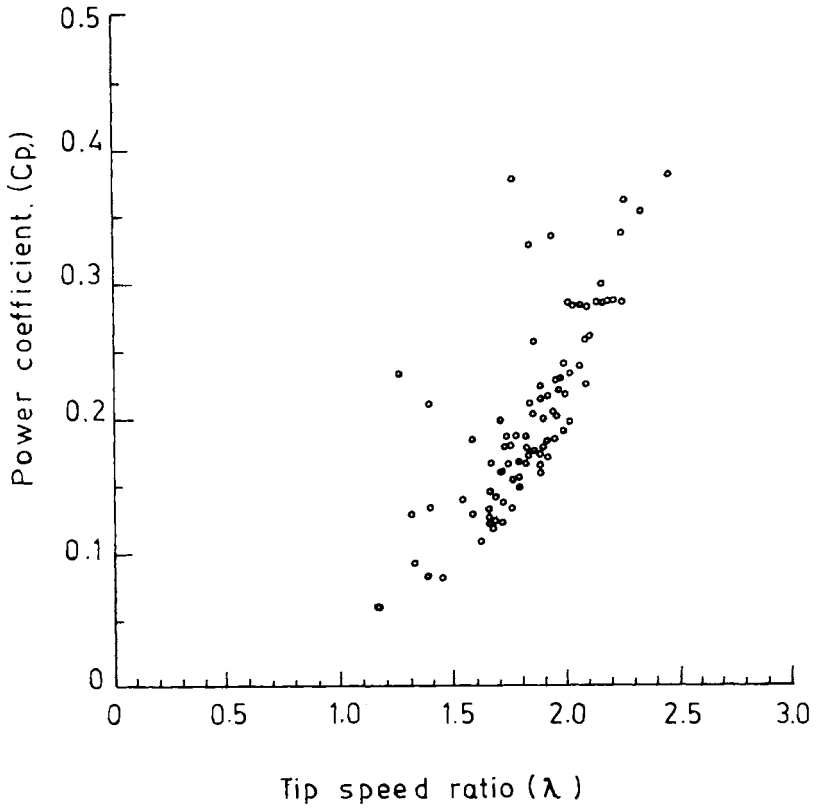
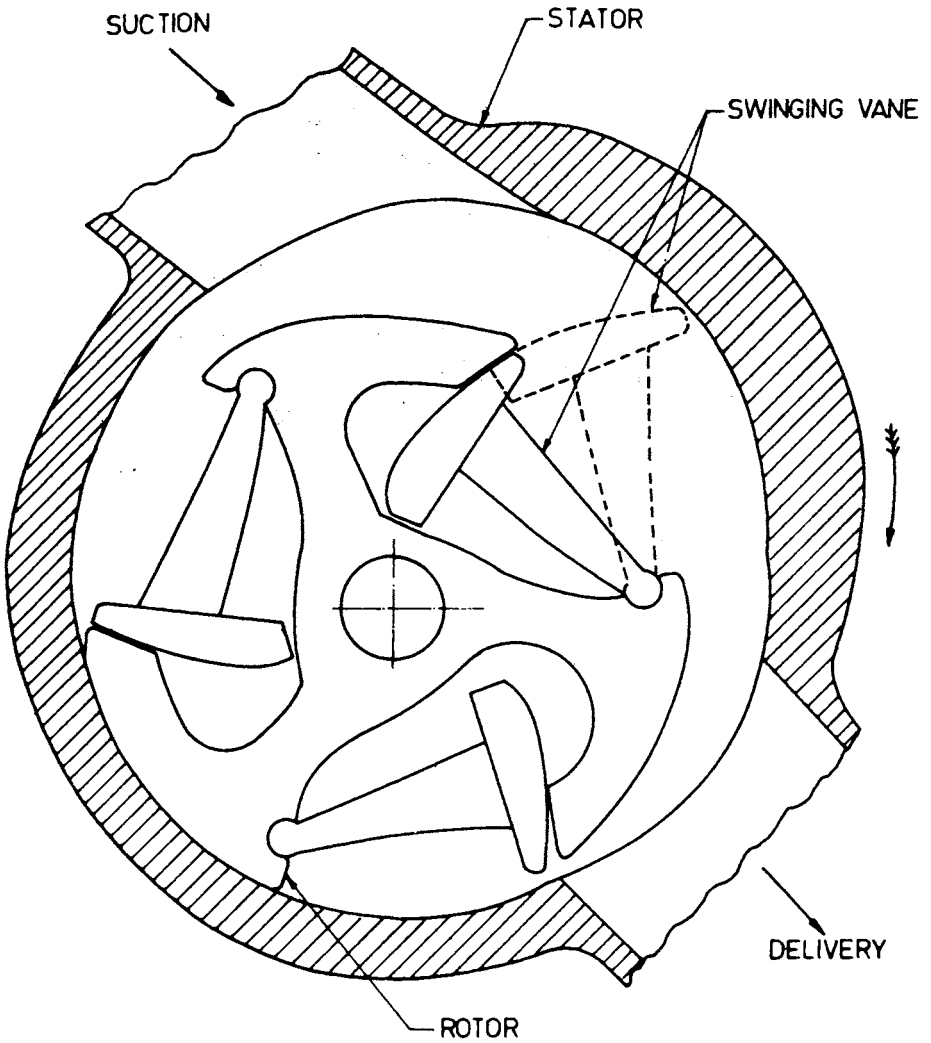


FIGURE 5: Schematic diagram of swinging vane rotary pump



**FIGURE 6: A view of the windpump test field in the campus of NAL.**

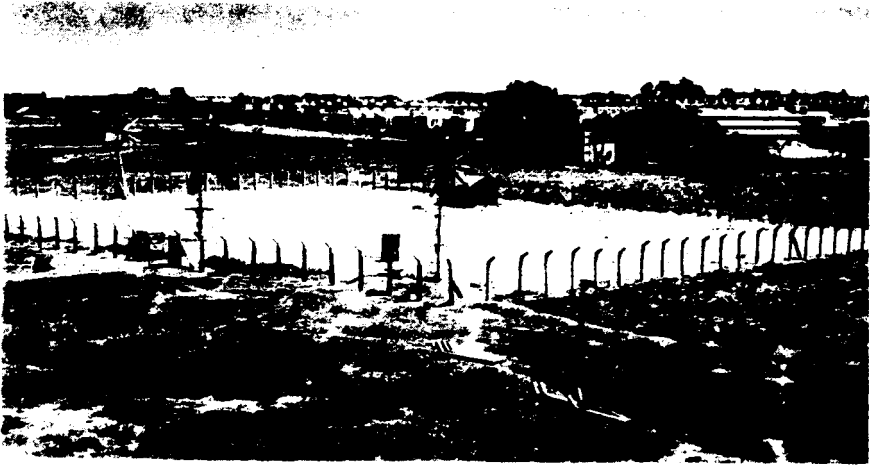
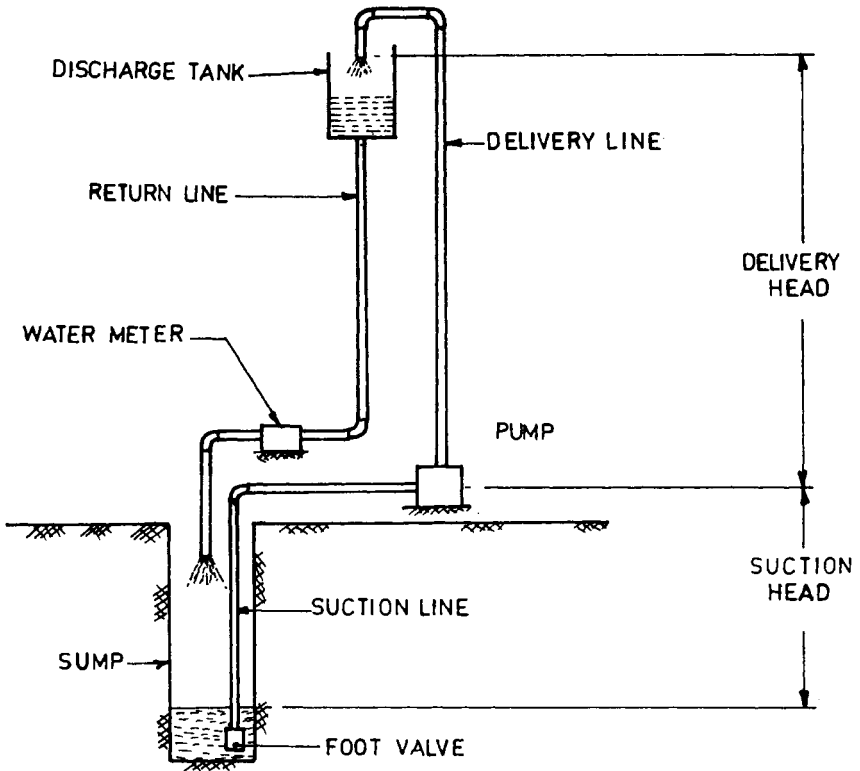
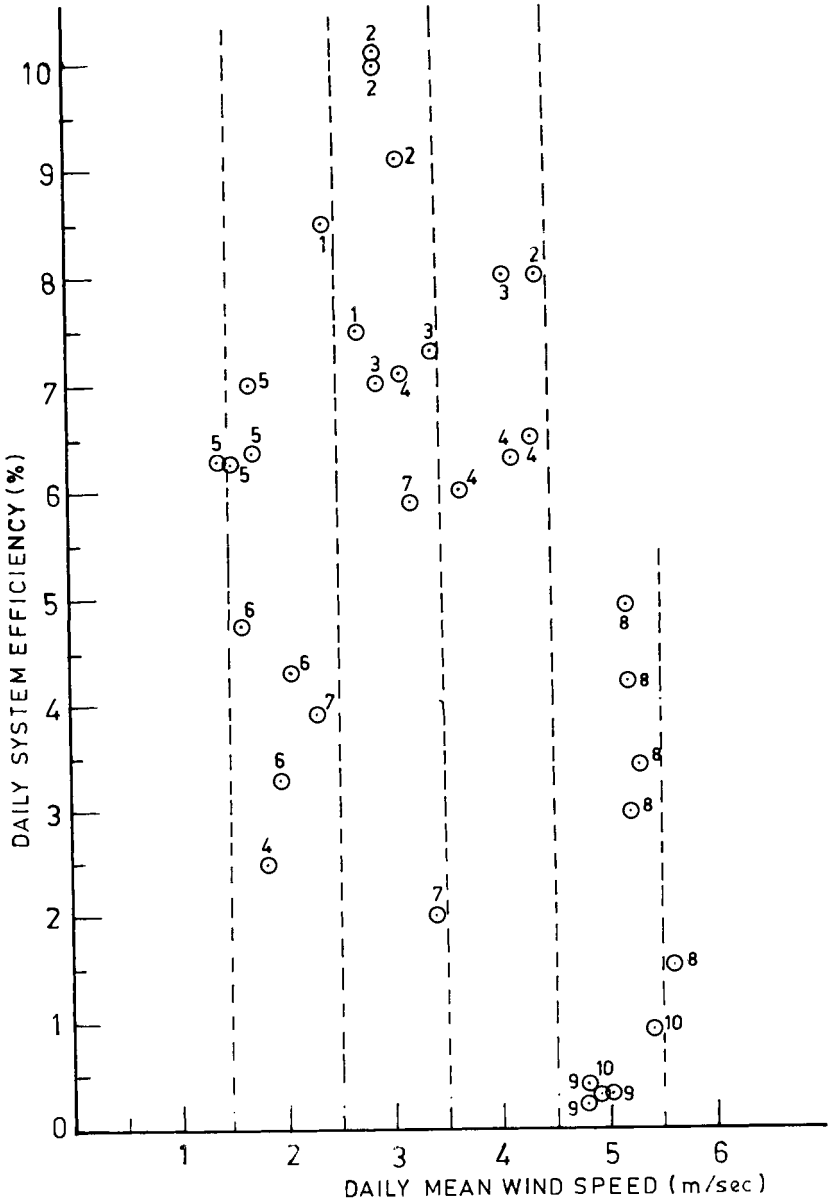


FIGURE 7: Schematic arrangement of water lifting in the test field



**FIGURE 8: Plot of daily system efficiency against daily mean wind speed**

The data are categorised on a weekly basis and identified by the number of the particular week ranging from 1 to 10 shown on 1 m/s intervals (1.5-2.5, 2.5-3.5, etc). A clear trend regarding fall in performance is observed. The information is in respect of a low cost piston pump (Venkatanarayana and Samaraj 1985).



## **WATER PUMPING WITH WINDMILLS IN ZIMBABWE**

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### **ABSTRACT**

The paper outlines the research that has been carried out to assess the available wind energy and water pumping performance of windmills in Zimbabwe. A summary of a cost comparison between a windpump, diesel, electric, solar and handpump is included. Results indicate that there are moderate to low winds over most areas of the country. The difference in performance figures of the same type and size of windmill located at different sites shows the importance of careful windmill siting covering, borehold yield, water demand and available windregime. A survey of windmill location within Zimbabwe indicated that windmills are more often sited where the money is than wind. Based on the cost comparison, windmills are more suitable for low energy water pumping requirements where hand or ox-driven water pumps would not be feasible. For the high energy pumping demands, ie large volumes of water at high heads, diesel or electric pumps are still more cost competitive.

### **INTRODUCTION**

Windmills have been used for centuries in America, Europe and Asia as a source of mechanical energy for water pumping, grain milling and more recently for generating electricity. There was a general decline in the use of wind energy after World War II due to the rapid development of the diesel engine, the availability of low-priced oil and widespread rural electrification by the national grids in the developed countries.

With the increase in the cost of petroleum based fuels of the 1970s, there has emerged a renewed interest into the application of windpower, especially in the oil-importing countries. Zimbabwe being one of these countries, has to find alternative energy sources to meet her major priorities for national development among which is rural water supply.

Water-pumping using windmills has been practised in Zimbabwe for several years mainly to supply water for domestic use and for livestock. As is general in most developing countries, the principal inhibiting factors for the popularity of windmills has been high capital costs of imported windpumps compared to diesel pumps, lack of expertise to install and maintain them and designs that are outdated and unsuitable for small-scale manufacture, thus limiting local production.

A survey of windmill useage throughout Zimbabwe showed that a few hundred windmills are in use today, mostly the Climax models imported from South Africa. Production has started in Zimbabwe so as to reduce the foreign exchange requirement for importation of windmills.

The paper outlines the research that has been carried out within Zimbabwe to evaluate (technically and economically) the viability of using windmills for water pumping and to determine the optimum windmachines necessary to suit the available windregimes.

## WIND ENERGY RESEARCH

Wind energy research in Zimbabwe focuses on collection and analysis of wind energy data, field monitoring of pumping performance of windmills on a daily basis and testing of various windmachines using field simulation techniques.

### Wind data

The Department of Meteorological Services maintains a daily record of windspeeds recorded at the various recording stations in Zimbabwe (Figure 1). Table 1 gives figures of mean surface winds from these records covering a period of 10 years up to 1973. Wind power obviously varies with time, ie by month, hour of the day and a short period of a few minutes. Hence the data for hourly averages presented in Table 1 may not be useful in establishing the energy in the wind. As the power in the wind varies as the cube of the windspeed, the absolute windpower is about treble the power calculated using the cube of the average windspeed. However, the average windspeed is still a reasonable good first guide when comparing different windmill sites (McNaughton 1982).

One of the important parameters to obtain from the wind data is the frequency and duration of occasions of nil power generation, ie when a specified threshold starting windspeed for a windmill was not attained. This information helps to establish whether a given site is suitable for a known type of windmill and to estimate the necessary storage capacity to ensure a continual water supply.

### Types of windmills

There are two principal types of windmills in use worldwide: the vertical and horizontal axis windmills. These two categories can also be divided into low-cost and high-cost commercial windmills.

Three types of low-cost windmills have been built and tested at the Institute of Agricultural Engineering (IAE). These are the Cretan sail-type windmill, the Savonius rotor and the multibladed horizontal axis windmill. The Cretan sail windmill failed after operating for a few months due to the heavy rotor and inability of the turntable to revolve freely. Attempts to get useful work out of the Savonius windmill built from oil-drum sections via a roller vane pump, piston pump and electric alternator were all unsuccessful in the absence of strong winds. The multibladed windmill was damaged after operating for two years owing to the lack of an efficient storm protection mechanism. It was therefore concluded that the low-cost small-scale windmill was inappropriate for Zimbabwe.

The majority of commercial windmills use in Zimbabwe are the Climax, multibladed horizontal-axis type imported from South Africa. These are sold in various sizes designated Nos 6, 8, 10, 12, 14 and 18, the designation number corresponding to the rotor diameter in feet.

### Wind power and windpump performance

Byabura-Kirya (1984) has outlined the procedure for estimating the theoretical power available in the wind and using it to predict the windmill and pump system output. The optimisation of the pumping performance of a windpump involves a complex exercise of windmill-pump matching. The main problem is due to the fact that the power in the wind is proportional to the cube of the windspeed

while the power from the pump commonly coupled to windmills in Zimbabwe (reciprocating piston pump) is proportional to its own speed. Ewens (1982) has found that sizing a pump so that the windmill starts in the average windspeed of the location and furling at the pump's maximum speed, and three times the average windspeed maximises the water output. The overall efficiency of a windpump is expressed usually as the overall coefficient of performance.

### Testing of windmills

#### Field tests

The Ministry of Energy, Water Resources and Development carried out a monitoring exercise of two windmills (Climax No 18) manufactured by Stewarts and Lloyds of Zimbabwe. Water pumped and windspeed were recorded at hourly intervals at one of the sites (A) and daily at the other site (B).

At site (A) an average of  $3.5\text{m}^3$  of water per day was pumped in an average windspeed of  $1.6\text{ms}^{-1}$  from a borehole 57m deep. At site (B)  $6.4\text{m}^3$  per day was pumped on average from a borehole 50m deep (total head 60m). The windspeed at the windmill site was not recorded but the average windspeed for the year 1983 obtained from the nearest Meteorological Station (Masvingo) was  $3.4\text{ms}^{-1}$ . Site (B) was a much better site than (A) with the windmill at (B) giving an output of about twice the value from an identical windmill at the other site.

#### Laboratory tests

The windmills were tested at the IAE using simulated borehole conditions. This has been achieved by passing the water from the pump through a pressure tank with trapped air. Different pumping heads are obtained by controlling the tank pressure and regulating the outflow by a remotely controlled solenoid valve.

Windspeed recorded on a multi-channel compiler instrument is obtained for hourly (day time only) and 24 hour day intervals. The data so obtained are used to compute the average daily, weekly, monthly and yearly windspeeds. Windspeed frequency histograms and speed-duration curves can be compiled using the same data. Figure 2 shows windspeed and energy distributions for a typical low and high windy month (1983 data). A computer program is being developed to derive a mathematical relationship between the data compiled at the testing site and a Meteorological Station 20km away. By recording the water pumped by the windmill at the same interval as the windspeed, the performance of the windmill can be established. Three types and sizes of windmill have been tested:

1. Acrobat (manufactured in Finland) - small size (1.2m diameter rotor), lightweight (30kg for mill and tower), ease of installation.
2. SMK (Zimbabwe) - medium size (3.05m diameter rotor), oil bath lubricated gearbox (3.5 : 1 ratio).
3. Climax No 18 (Zimbabwe) - large size mill (5.5 diameter rotor), direct drive transmission.

Performance curves for the three windpumps obtained over the testing period so far are presented in Figure 3.

In Zimbabwe, the water requirement for farmers (human and livestock), schools, hospitals and small rural communities generally varies from 3-20m<sup>3</sup>/day and the water table depth is 10-50m for deep boreholes. Using a baseline water demand of 5m<sup>3</sup>/day, it can be deduced from Figure 3 that the SMK windmill can meet the demand up to about 15 m water table depth, while the Climax No. 18 can meet the same demand up to 45 m depth. The Acrobat windmill designed for low lift water pumping does not meet the minimum rural community requirements and is thus not appropriate for Zimbabwe. Note that the average daily windspeed for the testing site at the IAE has been 3.1 ms<sup>-1</sup> for the two year testing period which is just short of the national average of 3.2 ms<sup>-1</sup>.

### COST OF WATER PUMPING WITH WINDMILLS

#### Cost of windmills

The three low cost windmills built at the IAE in 1979 cost from Z\$300 to Z\$650 (raised to 1984 prices using a steady 12% inflation rate). The commercial windmills (Climax models) imported from South Africa costs from Z\$2000 to Z\$8750 for the Nos. 8-18. The locally manufactured windmills Nos. 12 and 18 cost Z\$3625 and Z\$6100 respectively (1984 prices).

#### Cost comparison with other water pumping systems

Elliott (1983) carried out a cost comparison analysis between diesel, electricity, solar, wind, human and animal powering pumps. He considered pumping against various heads and pumping rates ranging from 3-60m and 10-1000 m<sup>3</sup> day<sup>-1</sup> respectively. The method used for the analysis was that developed by Medford (1980) to compare conventional to renewable energy sources. By this method, the present value of an energy system after a life span of the equipment is given by:

$$\text{Present value} = \text{Capital costs} + (\text{recurrent costs}) \times N$$

$$\text{Where } N = \frac{1}{a-r} (e^{(a-r)T} - 1)$$

a is the petroleum escalation and general inflation rate factor; e is the mathematical exponent = 2.718; r is the discount rate (decimal); and T is the time to obsolescence of the system (years).

Elliott established that windmills were not viable for high-volume water pumping requirements in Zimbabwe. In such situations, diesel or electric pumps are most cost competitive. But for low energy pumping, ie low volumes (less than 10 m<sup>3</sup>/day) and heads (less than 50m) and for rural locations some hundreds of miles from a developed town where the transport of fuel or extension of an electricity line would be prohibitive, the use of a windmill may be justifiable.

### EXTENT OF WINDMILL USE

A survey was carried out by the major windmill distributors in the country (Stewarts and Lloyds Ltd) to find out the location, present state and type of use of windmills. Most of the windmills in use up to 1983 were Nos 8-14 and located in commercial farming areas. They were generally used for cattle watering and supplying water for domestic needs. The depth of boreholes varied from 7m (23 ft) to 49m (160 ft) with an average depth of 24m (79 ft). The recorded estimates

of average daily output varied from 1140 to 9000 litres. The general view of users was that the windmills were a cheap and reliable source of power for water pumping besides a few complaints about the high initial costs and some occasional periods of insufficient wind at windmill sites.

### CONCLUSIONS

1. Because of the low windspeeds prevalent in Zimbabwe, the conventional multibladed farm windmill has proved the most successful.
2. Windmills should be used for low energy water pumping demands in remote rural locations in situations where hand, diesel or electric pumps would not be feasible. Careful selection of a site is required and ample storage should be allowed for to fully optimise the windmill output.
3. Local manufacture of windmills give them an advantage over other water pumping systems like diesel engines or solar powered machines as less foreign currency is required for importation.
4. There is a need for further coordinated research in the country to determine the optimum windmill types and sizes to suit the available wind regimes. More comprehensive economic analyses should be carried out to justify the use of windmills instead of hand, animal, diesel, electric or solar powered pumps.

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TABLE 1: Mean surface windspeeds over Zimbabwe (ms<sup>-1</sup>)

STATION	MONTH												YEAR
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	
Binga	2.5	2.4	2.5	2.6	2.5	2.5	2.2	2.6	3.0	3.4	3.0	2.8	2.7
Buffalo Range	2.6	2.2	2.3	2.0	2.9	2.9	2.0	2.5	3.2	3.5	3.1	2.8	2.5
Bulawayo (Goetz)	3.5	3.5	3.6	3.3	3.5	3.8	4.0	4.2	4.3	4.1	3.4	3.2	3.7
Chipinge	4.2	4.0	4.0	3.9	3.6	3.5	3.5	4.1	4.7	5.0	4.7	4.3	4.1
Chirundu	1.3	1.2	1.4	1.5	1.5	1.6	2.0	2.5	3.2	3.1	2.2	1.5	1.9
Masvingo	2.6	2.5	2.4	2.2	2.0	2.0	2.2	2.6	3.2	3.3	2.9	2.6	2.6
Kadoma	2.4	2.8	2.9	3.3	3.4	3.9	3.8	3.9	4.1	4.5	3.8	3.1	3.5
Grand Reef	1.9	1.9	1.7	1.7	1.4	1.3	1.6	2.2	2.9	3.2	2.7	2.2	2.1
Gweru	3.4	3.4	3.5	3.1	3.1	3.2	3.2	3.9	4.3	4.2	3.7	3.5	3.5
Inyanga	2.5	2.6	3.0	3.1	2.9	2.9	3.2	3.4	3.8	3.8	3.2	2.6	3.1
Kariba	1.6	1.6	1.6	1.9	2.0	2.0	2.0	2.3	2.8	3.1	2.5	1.9	2.1
Karoi	2.7	2.6	2.9	3.0	3.0	3.1	3.2	3.6	4.1	4.1	3.5	3.0	3.2
Kwekwe	2.1	2.2	2.6	2.5	2.6	2.7	2.7	2.8	3.2	3.3	2.7	2.3	2.6
Harare (Belvedere)	2.6	2.6	2.8	2.8	2.8	3.0	3.3	3.5	3.9	3.9	3.2	2.9	3.1
Kutsaga	3.1	3.1	3.3	3.3	3.2	3.4	3.5	4.0	4.5	4.7	3.9	3.5	3.7
Victoria Falls	2.1	2.1	2.3	2.1	2.1	2.1	2.3	2.7	2.5	3.1	2.8	2.3	2.4
<b>Country average</b>	<b>2.6</b>	<b>2.5</b>	<b>2.7</b>	<b>2.6</b>	<b>2.6</b>	<b>2.7</b>	<b>2.8</b>	<b>3.2</b>	<b>3.6</b>	<b>3.6</b>	<b>3.2</b>	<b>2.8</b>	<b>2.9</b>

Source: Climate Information Sheet No. 53, October 1974

FIGURE 1: Map of Zimbabwe showing met station distribution

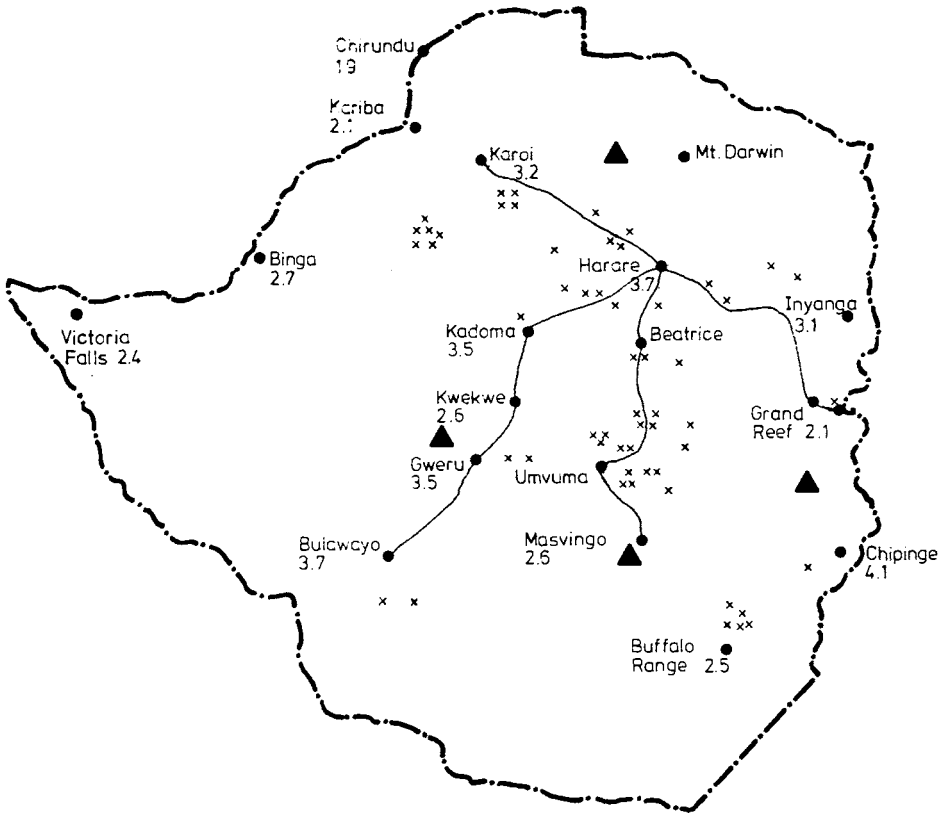


Figure 1: Map of Zimbabwe Showing Met Station Distribution.

x ——— Dot represents location of operational Windmill.

Binga ..... Annual mean windspeed  
2.7 (m/s)

**FIGURE 2: Windspeed and energy distributions for a typical low and high windy month**

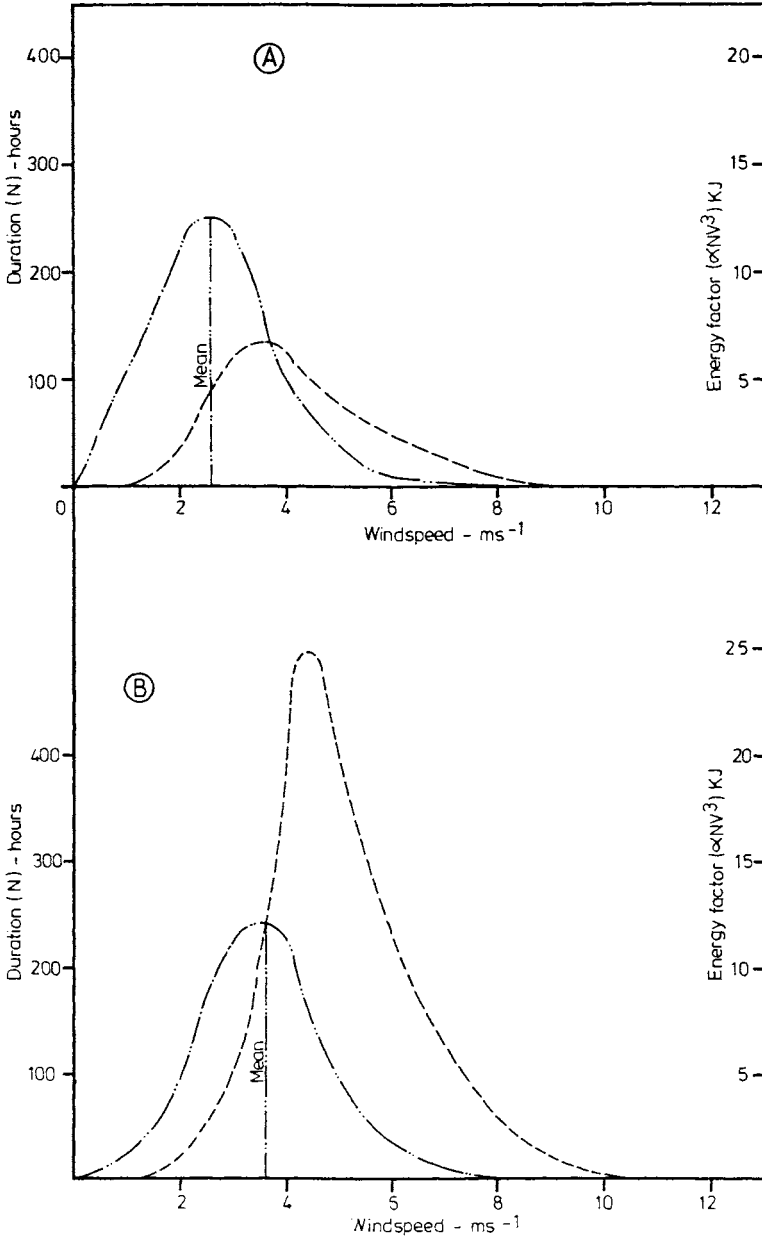
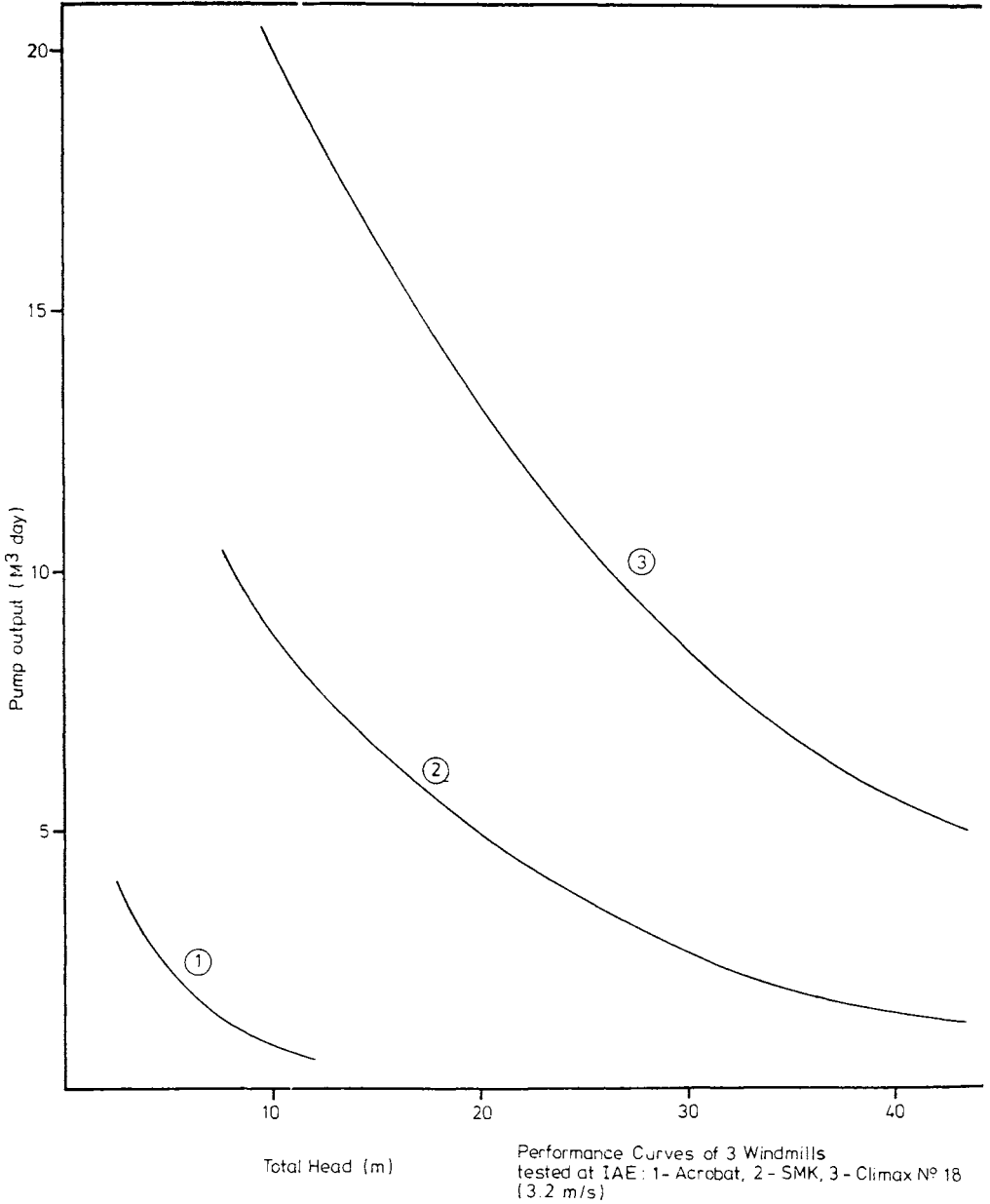


Figure 2 : Windspeed and energy distributions for a typical low and high windy month  
A : April B : September (1983, IAE.)

--- Energy  
-.-.- Windspeed

FIGURE 3: Performance curves of 3 windmills tested at IAE



## **A LOW-COST MICROPROCESSOR CONTROLLED MONITOR FOR WIND WATER PUMPING**

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### **ABSTRACT**

A simple system for monitoring wind water pumping performance which is suitable for a developing country is described. It is developed around a low-cost microprocessor system, Microprofessor 1B of Multitech Industrial Corporation, to monitor the wind speed, water flow and pump strokes. It has low initial and running costs, is easy to operate and maintain, requires minimum manual attention and has low and simple power requirements.

### **INTRODUCTION**

Wind energy is frequently used for pumping water. The choice of the windmill, the pump and the volume of the reservoir depends on the "wind regime" and the hydrogeological conditions. Therefore, to determine the best system, a pumping test with measurements of windspeed, pump strokes, and water output has to be carried out. A continuous monitoring of these parameters is, in most cases, very appropriate and sometimes necessary. It is useful to know both the distribution of wind speed and the average speed as a function of time. Since the power available from the wind is proportional to the cube of its speed (Le Gourieres' 1982) knowledge of distribution of wind speed is very important to estimate the available power. However, knowledge of wind speed distribution alone is not sufficient to fully understand the "wind regime".

A common method is to measure the wind speed distribution with a compiler (McGowan 1984). This sorts out the wind speed according to its magnitude and stores the information in "bins" as the number of time intervals. This generates a histogram of wind speed distribution from the site. Each bar of the histogram represents the amount of time the wind blew with a speed in each speed range (bin). For example, bin no 0 counts all minutes when the wind was blowing with a speed in the range  $0-2 \text{ kmh}^{-1}$ , bin no 1 counts minutes in the range  $2-4 \text{ kmh}^{-1}$  etc. The last bin represents the number of minutes during which the speed was above a certain limit. The weakness of this method is that it does not tell us, at what time of day or on what day of the week, the wind speed was maximum, minimum, productive, unproductive, etc. Therefore it is desirable to have an instrument which can record both the wind speed distribution histogram and the average speed as a function of time.

A nationwide network of monitoring stations, as set up in Botswana, is sometimes necessary to gather the data for the proper planning and utilisation of wind energy on a national scale. The instrumentation to acquire reliable data with minimum level of manual attention can be very expensive, especially for a developing country. The power requirements of the data acquisition system, maintenance, data retrieval and analysis can also be difficult problems.

Therefore, it is important to choose a monitoring system meeting the following criteria:

1. Low initial and running cost

2. must be easy to operate and maintain
3. requires only a minimum level of manual attention, and
4. low and easy power requirement.

Various low-cost microprocessor systems (like home computers), which require only a very low level of power, are now available. Such a microprocessor system along with a few easily available ICs can meet most of the above-mentioned criteria.

An example of a monitor built around a low-cost microprocessor system, Microprofessor MPF IB (Multitech Corporation) is described here. This design can be adapted to other Z80 microprocessor systems like the Sinclair Spectrum without much difficulty. Special care is taken to minimise the number of components and to use easily available ICs. The number of channels are limited to three (which can be increased if necessary), to monitor wind speed, pump stroke and rate of flow of water.

The software (details available from the author) provides histograms for each parameter at every fourth interval with a sampling interval of one second. This has the advantage of continuous monitoring to give the average data as a function of time, while providing a detailed histogram of the distribution. At this rate, a C90 audio cassette (one side) can run for about a month without any attention. As indicated later in this paper, the software can easily be changed to have any convenient histogram and sampling intervals.

Following a general description of the system, the hardware and the software of the system are discussed. This is followed by a description of the loading of the program, data acquisition and retrieval and the power requirements of the system. Finally, the initial and running cost estimates are presented.

### DESCRIPTION OF THE SYSTEM

Figure 1 shows a block diagram of the system. The sensors used in the present system are: a cup anemometer for wind speed, a flow meter for the water output, and a microswitch for the pump stroke. The cup anemometer has a reed switch operated by a set of four magnets rotating with cups. The switching "on" and "off" of the switches within all the three sensors are converted into standard TTL pulses by Schmidt triggers. The number of pulses produced in a given time interval is proportional to the magnitude of the parameter monitored. Three separate 8-bit binary counters count the pulses for a pre-determined interval of time (one second in the present case) referred to here as the sampling interval.

At the end of this interval, the counts are transferred to some temporary storage called "buffer". Within a few microseconds, the counters are cleared and counting starts again. In the meantime, the microcomputer reads the buffers, one after the other (and once in the sampling interval), and increments the content of an appropriate "bin" whose position represents the magnitude of the parameter monitored. Each "bin" is assigned to two successive bytes of the memory, so that the maximum number each bin can hold is 65,536. A block of 66 memory locations are reserved for each parameter, representing 33 bins. If the magnitude of the parameter is greater than 32 counts per second, it will also be registered in bin No 32.

The data recorded in bins 0-32 thus represent a histogram of the distribution. The histogram data for the three parameters are recorded automatically on an

audio cassette tape at regular intervals of time. This interval, denoted in the text as "histogram interval", in the present setup is 4 hours. After this interval the memory is cleared and a new histogram is recorded. In this way, a continuous record is obtained, while keeping the advantage of histogram records. The cassette recorder switches on automatically only six seconds before the recording and switches off when the recording is over, to save on power.

## HARDWARE

Figure 2 shows a detailed circuit diagram of the monitoring system. The output of ICI (7413) is counted by two 4-bit binary counters (7493) in series forming an 8-bit counter. The clear/count control signal is provided by PA0 - bit 0 of Port A of the Z80 PIO chip. The output of the 8-bit counter is latched by the respective tri-state buffer - IC 4, 5, or 6 (74LS373) at the end of the sampling interval. The latching is done by the signal from PAL. The tri-state buffers are enabled by the control signals from PA2, PA3, and PA4 one after the other. The data on the data bus are read by the microprocessor from Port B of the Z80 PIO chip. Control signal from PA5 controls the power supply switch of the tape recorder through an opto-isolator IC7 and a relay.

Microprocessor MPF 1B is the microcomputer controlling all the operations and storing the data temporarily. It is a simple system based on the micro-processor Z80 and having 2K RAM, 2K ROM, a hexadecimal keyboard (with some function keys), and a six digit read-out. The 2k-ROM holds a sophisticated monitor including routines for tape write and read. A complete listing of this program is available with the system. The System also has sockets for an EPROM, the Z80 counter-timer IC (CTC), and the Z80 Parallel Input/Output IX (PIO). The CTC and PIO are daisy-chained with the CTC having the higher interrupt priority. The CTC and PIO signals are accessed through the edge connector P<sub>2</sub> on the system board.

The function of the Z80 CTC in this design is to interrupt the micro-processor at regular intervals of time, to perform the Interrupt Service Routine (ISR) which acquires the data from PIO Port B and increments the count of an appropriate bin (two-byte memory locations). The CTC has four independent channels which can operate either in the counter mode or timer mode. In the counter mode, the CTC accepts and counts pulses from an external source. The CTC can be set to interrupt the microprocessor after a certain number of counts have occurred. In the timer mode, the CTC counts the pulses from the system clock. In the present design, channel 2 is programmed to operate as a timer and channels 1 present and 0 respectively. Channel 0 sends the interrupt signals to the microprocessor. The interrupt period (sampling interval) is, thus, given by (system clock period) x (Pre Pascal of channel 2) x (Time constant of channel 2) x (Time constant of channel 1) x (Time constant of channel 0); in this program one second.

The Z80 PIO has two bi-directional ports, Port A and Port B. In the design described here, Port A is set in the control mode and Port B in the input mode. Only 6 out of 8 available control signals from Port A (PA0-PA5) are used here.

## SOFTWARE

As mentioned before it is desirable to know both the distribution and the average value of a parameter as a function of time. The software described here is a compromise between these two requirements. It samples the data every second

and stores it as a histogram. A new histogram is generated every four hours. Adding these histograms, it is possible to get the distribution for a day, a week or a month. The average value of each distribution also provides wind speed as a function of time. Both the sampling interval and histogram interval can be changed easily to suit a situation where one of the above mentioned requirements becomes more important.

The program consists of three parts:

1. Initialisation routine
2. Interrupt service routine
3. The routine for recording on an audio tape.

### Initialisation routine

This routine resides in memory locations 1800H - 1838H, when the program is loaded into the machine. The first part of the routine allocates memory spaces for the three "compilers" - wind (1A00H - 1A40H), pump strokes (1A44H - 1A84H), and water flow (1A88H - 1AC8H). Memory locations 1A00H and 1A01H are assigned as the low and high bytes of bin 0 of the wind compiler, 1A02H and 1A03H as the low and high bytes of bin 1 of the same compiler, etc.

The second part specifies the sampling interval, histogram interval and the end of the tape. A software solution to detect the end of the tape is preferred here over a hardware solution, as it is safer and reduces the component count. By changing the sampling location (one second here) the histogram interval and the total time for a single run will also be changed. For example, if the sampling interval alone is changed to 0.5s, the histogram interval will be reduced to 2 hours and the total time for a single run with a C90 tape will be about 15 days.

### Interrupt service routine

This part of the routine scans the counters of the wind, pump stroke and waterflow channels and receives the data. If a data item is not less than 32, a value of 32 is assigned to it. The processor uses this number (<32) to find a corresponding set of locations (bin) and increments its content by one. Each bin is 2-byte wide so that it can hold up to  $256 \times 256 = 65,536$ . After reading the wind channel, it passes on to pump stroke channel and then waterflow channel. During the operation, the counters are still counting. The counters stop counting only for a few micro seconds between the instructions. The ISR is repeated every second (or the sampling time).

### Tape routine

When the data counter reaches zero, ie after 14,400 sampling intervals = 4h, the tape routine takes over. The power of the tape recorder is switched on and the system then waits for 6s to stabilise. A file number is automatically assigned. The first file number is the initial setting of the DE register-pair, 180 in the present case. The next file number will be 179 and so on. Instructions from 18FCH to 1907H specifies the memory area to be copied on to the tape. The program then calls a sub-routine from the Microprofessor monitor (instruction at 191H) to record the data on to the tape. After copying the three histograms, the tape recorder switches off automatically and the memory area in the micro computer is cleared. It then returns to perform another four-hour run. During tape-recording which lasts about 1 min, the counters stop counting.

### **PROGRAMME ENTRY**

The machine code in hexadecimal notation is first loaded manually, using the hexadecimal keys of Microprofessor. (For details of loading a program, refer to the Microprofessor User's Manual.) Once the whole program is typed into the memory of the system, it can be copied onto a cassette tape. Since there is an extra socket provided for an EPROM on the system board, the program can be copied and stored permanently in an EPROM IC.

### **DATA ACQUISITION AND RETRIEVAL**

After loading the program from the tape, alterations necessary to assign sampling interval, histogram interval, and tape length, can be made by entering the appropriate numbers in the locations mentioned earlier. The data acquisition can be stopped at any time by pressing the reset key and the stored data examined. The data recorded on the tape can be read back into the memory of the system, one file at a time (one histogram for each channel) and displayed by the six-digit read out. A low-cost thermal printer (PRT-MPF-1) is available from the manufacturer of Microprofessor to obtain a printout of the data. A more efficient method is to communicate the data directly into the memory of another computer (used for analysis) through an interface between the Z80 P10 and the user port of the microcomputer.

### **POWER SUPPLY**

Microprofessor requires only unregulated power of between 7 and 24V. The interface needs 5V regulated power which is obtained from the same unregulated power supply of 7 to 24V using the circuit shown in Figure 3. Therefore, the whole system can be powered from a 12V car battery which can be charged by solar cells. The tape recorder requires an additional 6V source.

### **CONCLUSION**

The complete system, excluding the battery and the audiocassette recorder weighs only about a kilogram and has a simple power requirement. The maximum current drawn is 0.5A. These factors make the system ideal for field use. The components used are minimum and easily available. The initial and running costs are very low (Table 1). With a proper housing, it can accumulate data for several weeks without the attention of an operator. A prototype of this system was built and found to run for several weeks under laboratory conditions.

### **ACKNOWLEDGEMENTS**

The contributions of Dr S Idzenga and Mr M Hamlyn at various stages of this project are gratefully acknowledged. The author is also grateful to Dr Car P Zietlow and Miss G M Masire of Botswana Renewable Energy Technology Project for their support and assistance with the sensors and to the University of Botswana Research and Publications Committee for the financial support.

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**TABLE 1: An estimate of initial costs**

	<b>£</b>
Microprofessor MPF-IB	100
ICs, Connectors and Cable	25
Tape recorder with tape, and recording cable	<u>35</u>
<b>Total</b>	<b><u>£160</u></b>

(Anemometer, flowmeter and battery are not included in the above estimate)

**An estimate of running cost**

No running cost is expected other than the cost of cassette tapes and charging of batteries.

FIGURE 1: Block diagram of the monitor

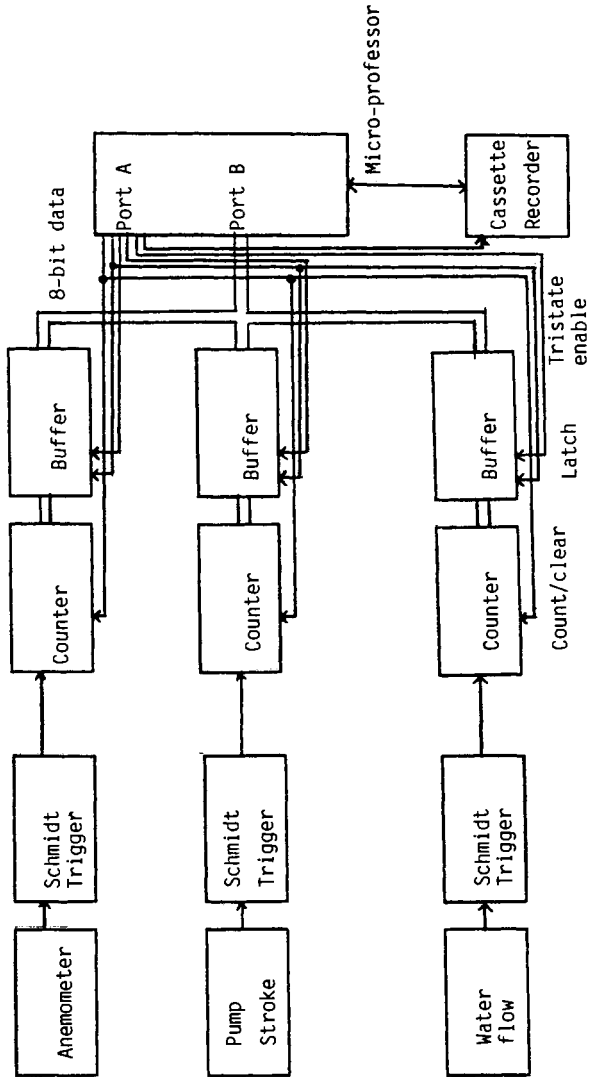


Fig. 1 Block diagram of the monitor

**FIGURE 2: Circuit diagram of the monitor**

(only one channel is shown)

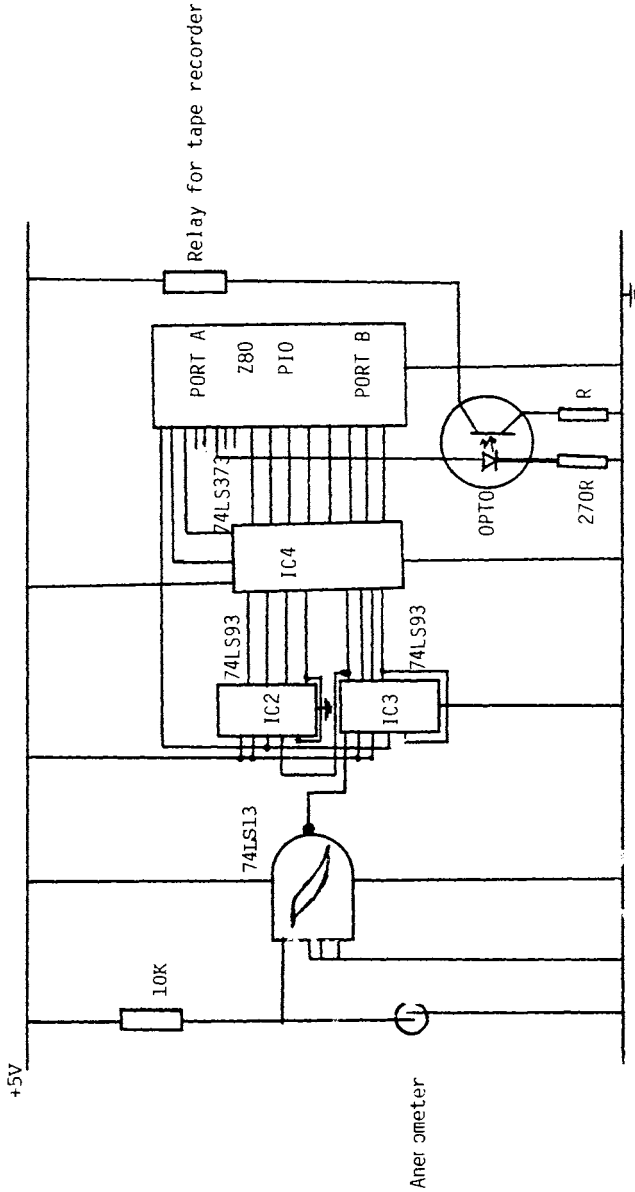
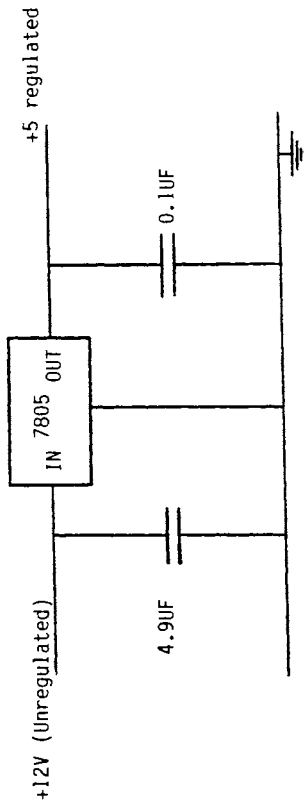


Fig 2. Circuit diagram of the monitor  
(only one channel is shown)

FIGURE 3: Power supply for the monitor



## WIND ENERGY RESEARCH AND APPLICATION IN MAURITIUS

Y Boodhoo, Meteorological Service, Vacoas

### INTRODUCTION

As part of the Government of Mauritius plan to diversify its use of alternative energy sources, the Mauritius Meteorological Office (MMO) initiated a programme to evaluate both the wind and solar energy potential of Mauritius. This paper describes the attempts to assess wind power.

A number of problems were encountered, in particular the use of anemograms which meant that compilation of hourly means was very time consuming. Secondly initial siting of stations in agricultural areas raised doubts as to whether this would provide a comprehensive picture of the windpower potential of Mauritius. Thus following initial work using data collected in 1980, the Government agreed to support a UNDP project to make a proper evaluation to conclude all the windiest sites in Mauritius.

Following a brief explanation of the calculation of wind power, this paper describes the data obtained in 1980 from the original weather stations. Finally the preliminary findings for the comprehensive evaluation now in progress will be presented.

### WIND POWER

The theory behind wind power is simple (Golding 1976). The kinetic energy of the air in motion is expressed by

$$P = \frac{1}{2} MV^2 \quad (1)$$

Where M is the mass and V, the velocity of the air parcel. If D is the density of air passing through a cross-sectional area of A then the mass of that air in unit time is given by

$$M = DAV \quad (2)$$

hence the kinetic energy per unit time is given by

$$P = \frac{1}{2} MV^2 = \frac{1}{2} DAV^3 \quad (3)$$

D can be computed for the standard atmospheric pressure 1000 H<sub>p</sub>, absolute temperature 290°K, using the gas equation in the form

$$D = \frac{P}{RT} = 1.2 \text{ kg per cubic metre} \quad (4)$$

Putnam (1984) suggested 35% as the maximum fraction of power in the wind which could be extracted. Golding (1976) has shown that this efficiency can be increased to 59.3%. With this efficiency, equation (3) becomes

$$P = 0.593 KAV^3 \quad (5)$$

As suggested by Rene (1981), power in the wind can also be expressed by

$$P = \frac{1}{2} - D \frac{C}{j=1} F_j V_j^3 \quad (6)$$

Where C is number of wind speed classes, F<sub>j</sub> the frequency of occurrence of winds in the j<sup>th</sup> class, and V<sub>j</sub> the median wind speed of the j<sup>th</sup> class. The bar in equation (6) indicated average values. With hourly wind speeds available, Rene asserts that the power potential available in the wind is simply expressed by

$$P = 0.955 DV^3 \quad (7)$$

Equation (7) can be used upon the assumption that the frequency distribution is a Rayleigh one.

### ANALYSIS OF 1980 DATA

Raw data from anemograms for seven stations were used to obtain hourly means which can be used to compute simple statistical data required to estimate available wind power and wind speed, treated here simply as a scalar quantity, and the atmospheric pressure.

Raw data from anemograms from seven stations were used to obtain hourly means which are then used to compute simple statistical parameters like correlation coefficients and standard deviations. The seven stations considered are mostly inland the they are all the same standard height of 10 metres above ground level. Medine, Plaisance and Digue Seche are respectively 1, 2 and 3 km from the sea shore. Vacoas is at the site of the Main Meteorological Office, whereas Plaisance is located on the premises of the airport. Table 1 gives the mean monthly wind speeds at each station.

To find the frequency of anticyclones passing near Mauritius in 1980, atmospheric pressure at 1600 hours, local time, of one station, Plaisance was plotted against days of the year. It should be noted that the pressure fluctuation at any point over the island would give the same result since the island is small compared to a synoptic scale of an anticyclone. Changes in atmospheric pressure at any one point would be felt almost anywhere within minutes. The pressure variation, coupled with the variation of the mean 10 minutes wind speed at the same synoptic hour, gives an indication of the meteorological situation.

The criteria for determining the exit of an anticyclone and the entry of another one are:

- (a) a wind speed of less than 2.5 m/sec for two days, and/or
- (b) a fairly steep fall parallel to the low wind.

Daily synoptic charts for this area have been consulted to back up the conclusions reached above. The frequency of anticyclones affecting Mauritius has been found to be 11.4 days. Out of these 3 are lull days on an average. Using the above criteria a back up system must be made ready for 3 out of every 11.4 days (Boodhoo 1984).

The results are displayed in the form of a wind energy map in Figure 1. Contrary to expectations and assumptions long established at the Meteorological Office of Mauritius, very promising results have been found along the North East coast of

Mauritius, whereas formerly it was taken for granted that the wind speed was greatest over the high grounds and to the south east. This finding has been confirmed by the more extensive survey described below.

### **UNDP WIND ENERGY EVALUATION**

As mentioned in the introduction, the positioning of weather stations used in the 1980 survey did not cover all the potentially important areas of the island. The UNDP financed programme, implemented by the Meteorological Service is being conducted to look more comprehensively at the feasibility of utilising wind resources to supplement existing electrical generation and as far as possible to meet future increased electric power needs in Mauritius.

Ten sites (Figure 2) were selected where anemometers were erected. These were mostly along the south, south east and north eastern coasts and a few over the Central Plateau. These sites had been shortlisted from more than 30 sites chosen according to meteorological characteristics. At one location, Bigara, four sensors were installed along a 200 metre tower at the 10, 30, 72 and 122 metre levels. The aim here was to find the wind profile inland as any generator installed would most certainly be above the standard 10-metre level at which anemometers are generally installed.

The instruments in the field consist of a cup anemometer and wind vane combination manufactured by Weather Measure Corporation (Model W200 SP). The anemometers were brought to Mauritius already calibrated by the contractor, the Battelle Memorial Institute in Washington State, USA. Each anemometer was connected to a data field unit (the Wind Prospector's Instrument, abbreviated WPI) which performs field processing of the data and stores the results (Figure 3).

The data are collected from the sites each month although the storage capacity of the WPI is about 40 days. The data extracted from the WPI is stored on an audiocassette tape. Processing is greatly simplified since the WPI does a considerable amount of processing. The instrument acquires wind speed and direction data once every 1.5 seconds. These data are averaged over a 6 min interval, then processed by the WPI to yield the following wind statistics:

- (a) Wind speed frequency histogram.
- (b) Joint distribution of wind speed versus wind direction.
- (c) Joint distribution of wind speed versus time of day.
- (d) Joint distribution of wind direction versus time of day.
- (e) Turbulence intensity frequency histogram (using standard deviations based on the 1.5 second sampling).

The WPI also records the peak gust speed (between data extractions).

For final analysis audiocassettes are read through a demodulator into the graphics terminal of a Hewlett-Packard both at Battelle and at the Meteorological Office.

## RESULTS AND CONCLUSIONS

Table 2 gives some of the main characteristics over the period August 1983 - June 1984. Figure 2 presents the same results in the form of an energy map. Coastal areas are by far the windiest places of Mauritius with the southern, eastern and even north eastern coasts receiving the most wind energy flux. As mentioned earlier, this is contrary to what has been assumed at the Mauritius Meteorological Office. Formerly it was taken for granted that the south east coast which falls directly under the prevailing south east trade winds and the high grounds are the windiest. However, the trade winds striking the island which acts as an obstacle, are deflected sideways thus depriving the higher central areas of the island of most of its winds (Figure 4).

The wind profile at Bigara shows that friction greatly reduces the wind close to the ground. However, above 30 metres wind speed becomes more or less constant (Figure 5) at nearly twice the speed measured at the 10 metre level. Since wind energy is directly proportional to the cube of the speed, the wind power will be many times higher at 30 than 10 metres level. At the 10 metre level the windiest sites are along the coasts where the investigation is being carried on. But the results at Bigara are important because most generators are located around the 30 metre level. Bigara could also be the best candidate site as it carries the least percentage of calm periods (between 3 and 4% of the time).

Although the survey demonstrates considerable potential for a wind energy exploitation programme in Mauritius, a number of points need to be borne in mind.

- a. The investment cost is extremely high and any generator should repay the investment in not less than 20 years. This applies particularly to a case like Mauritius where 99% of the land is electrified.
- b. It must be made certain that the very high winds and gusts experienced during tropical cyclones will not damage the generators. So far very few, if any, generators even at the famous test centre in Colorado, USA have been exposed to and resisted gusts of the order of 81 m/sec as experienced during cyclones in Mauritius.

If wind generators are installed, these should be limited to medium capacity and used for subsidiary purposes, eg pumping water or catering for the needs of small enterprises. However if a suitable cyclone-proof (or nearly so) system becomes available, wind energy could be used to supply between 5% and 10% of the total energy needs (which amounts to around 100 Mega Watts at present) of Mauritius.

## RODRIGUES

A similar investigation has been conducted of the wind regime over the island of Rodrigues. As a result a small 2.5 Kw generator has been installed at Anse Quitar. The performance of this generator has been very encouraging. The Government of Mauritius is now considering the feasibility of installing four similar generators at Port Sud Est, Anse Ally, Riviere Coco, and Les Graviers. Wind speeds are relatively higher (Table 3) than over Mauritius.

Unlike Mauritius the terrain of Rodrigues is so varied that despite its small size (roughly 109 km<sup>2</sup>) electrification, which is extremely expensive, is confined to

only the main areas. Hence wind may have an important role in supplying energy on this island. The wind pump at Anse Quito was primarily intended to pump water from boreholes to a reservoir for distribution to households. So encouraging are the results that the water storage capacity has been doubled. Even so, there is a surplus of electrical energy which is shortly to be distributed to an agglomeration of about 18 houses in Anse Quito. The total pumping system output from the date of commissioning on 24 May 1983 up to the end of April 1984 was approximately 1.7 million gallons of water pumped over a period of 1788 hours of operation. These figures have more than doubled up to the present.

### CONCLUSION

The survey of Mauritius has shown a major potential for exploiting wind energy at various sites. However, the wind energy programme needs to consider its exploitation in relation to the energy resources and capital investment costs. The case for exploiting wind energy is much clearer for Rodrigues, where electricity generation by other means is less universally available.

This wind energy programme is still in progress and data presented here are only the preliminary findings. However, the changes should be so small as not to substantially affect the conclusions.

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**TABLE 1: Correlation matrix for daily mean speed for 1980**

<b>Stations</b>	<b>Vacoas</b>	<b>Plaisance</b>	<b>FUEL</b>	<b>D Seche</b>	<b>MDA</b>	<b>Medine</b>	
Plaisance	0.79						
FUEL	0.31	0.30					
D Seche	0.29	0.31	0.51				
Mon Desert Alma	0.32	0.33	0.63	0.82			
Medine	0.31	0.18	0.61	0.44	0.52		
Pamplemousse	0.29	0.23	0.66	0.76	0.83	0.67	

**TABLE 2: Standard deviation values**

<b>Station</b>	<b>Vacoas</b>	<b>Plaisance</b>	<b>FUEL</b>	<b>D Seche</b>	<b>MDA</b>	<b>Medine</b>	<b>Pamplemousse</b>
Standard deviation	0.65	0.87	1.82	1.42	1.37	1.23	1.28

**TABLE 3: Mean monthly wind speed at each station using 1980 data**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Vacoas	4.1	3.7	3.8	2.9	3.3	3.7	4.0	4.0	3.9	3.5	3.5	3.2
Plaisance	3.5	3.1	3.1	2.2	2.9	3.8	4.1	4.0	3.8	3.3	3.2	3.0
Pamplemousse	3.9	5.3	4.2	2.6	3.3	2.2	2.8	3.4	3.7	3.1	3.6	3.1
FUEL	3.4	4.2	3.0	2.8	3.4	3.5	4.4	4.2	3.9	4.1	3.2	2.6
D Seche	4.3	4.7	3.6	2.8	3.4	2.9	3.1	4.1	4.7	4.2	4.7	3.9
MDA	6.1	5.0	4.3	2.8	3.9	3.1	4.4	4.9	4.3	2.2	4.6	4.5
Medine	3.9	5.6	4.6	3.2	4.3	3.1	3.3	3.5	3.0	3.0	2.3	1.9

**TABLE 4: Wind characteristics over Mauritius, August 1983 - June 1984**

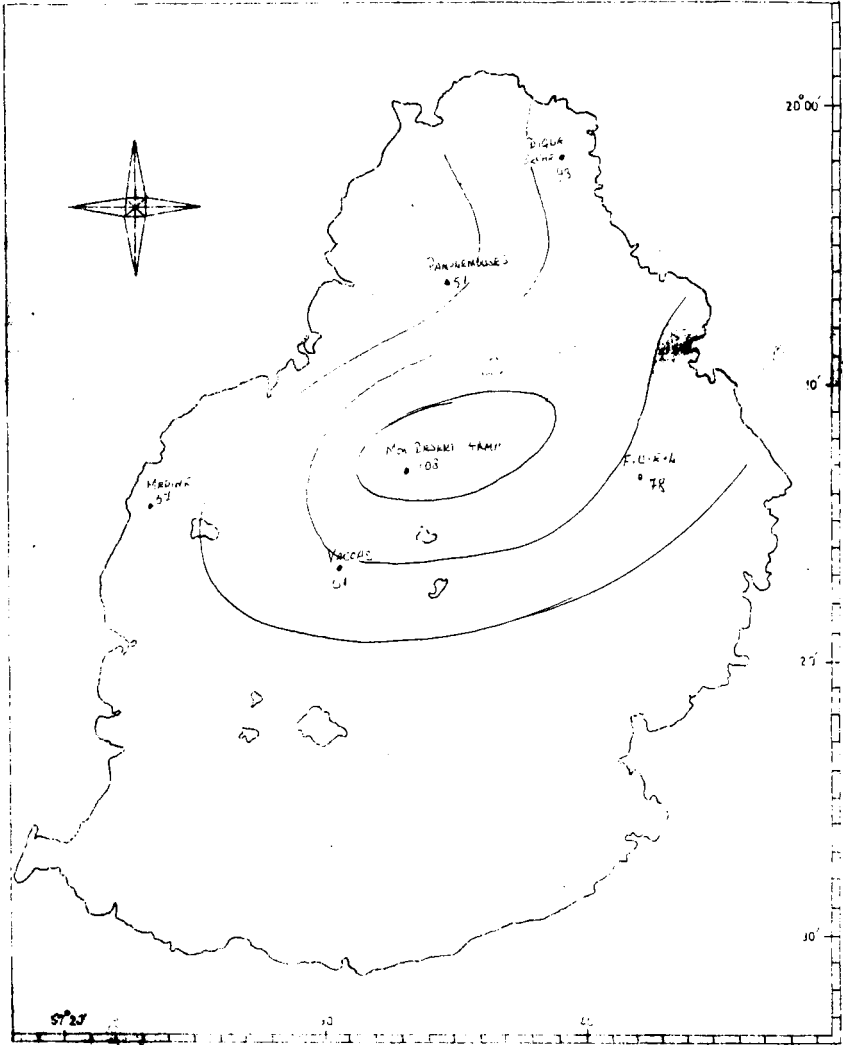
<b>Station</b>	<b>Mean speed (m/s)</b>	<b>Standard deviation</b>	<b>Mean Energy flux (w/m<sup>2</sup>)</b>	<b>Calm (% of time wind speed 2 m/s)</b>
Grand Bassin	5.14	1.96	112.65	6.87
Bois Cheri	3.6	1.68	44.0	19.37
Gris Gris	6.07	2.55	216.77	3.17
St Felix	4.11	2.0	74.53	18.11
B Ombre	5.0	2.62	154.6	22.02
U Park	3.68	1.89	54.7	24.44
G Port	5.38	2.72	199.4	18.70
Palmar	4.66	1.72	82.9	8.9
St Antoine	5.21	2.23	151.82	12.55
MGI	3.95	1.94	72.58	30.23
Bigara* (32 ft)	3.24	1.82	140.24	3.00
Bigara (100 ft)	6.15	2.15	184.42	4.02
Bigara (240 ft)	7.57	2.98	384.35	4.97
Bigara (400 ft)	8.1	3.36	570.66	4.23

\* Four anemometers were installed on a tall tower at Bigara on the 32, 100, 240 and 400 ft levels.

**TABLE 5: Winds over Rodrigues**

<b>Area</b>	<b>Mean wind speed (m/s)</b>
Anse Ally	4.7
Les Gravieres	5.9
Port Sud Est	9.5
Riviere Coco	6.4
Pointe Canon	10.2

**FIGURE 1: Location of anemometers for the Meteorological Service  
Isochrone of wind power ( $W/m^2$ ) for 1980**



**FIGURE 2: Location of new sites  
Isochrone of wind power ( $W/m^2$ ) based on UNDP financed programme**

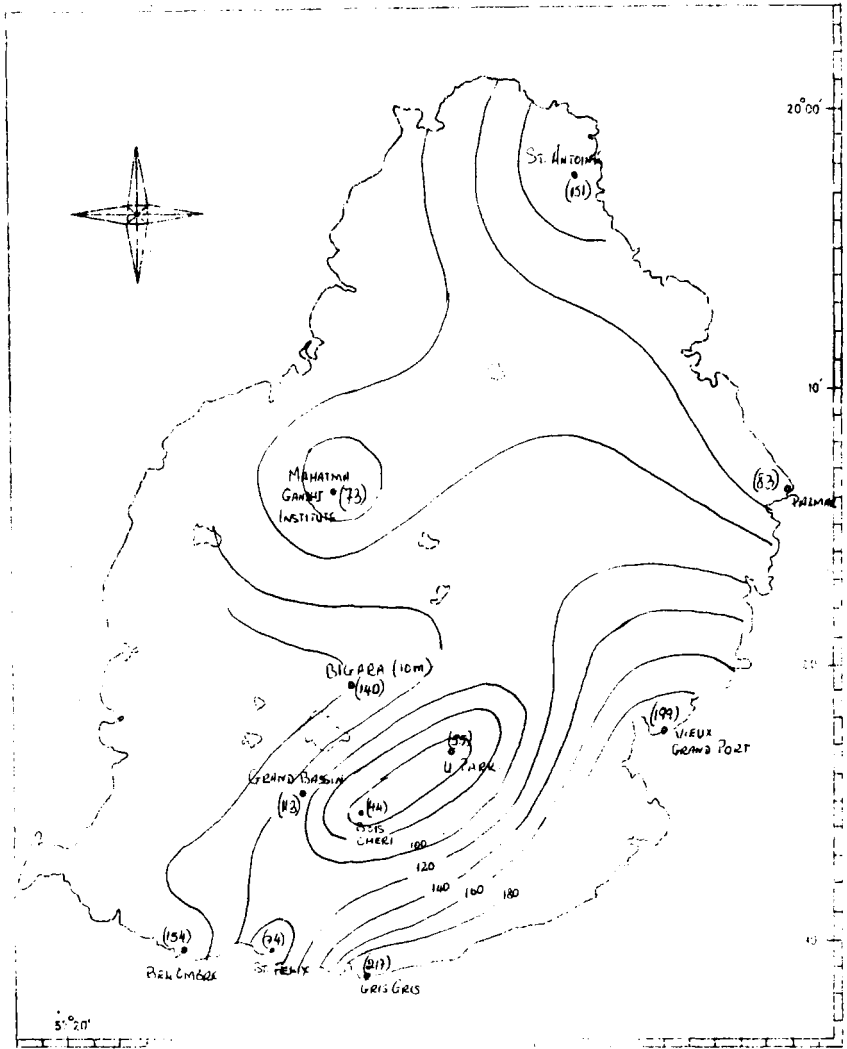


FIGURE 3: The system - its parts

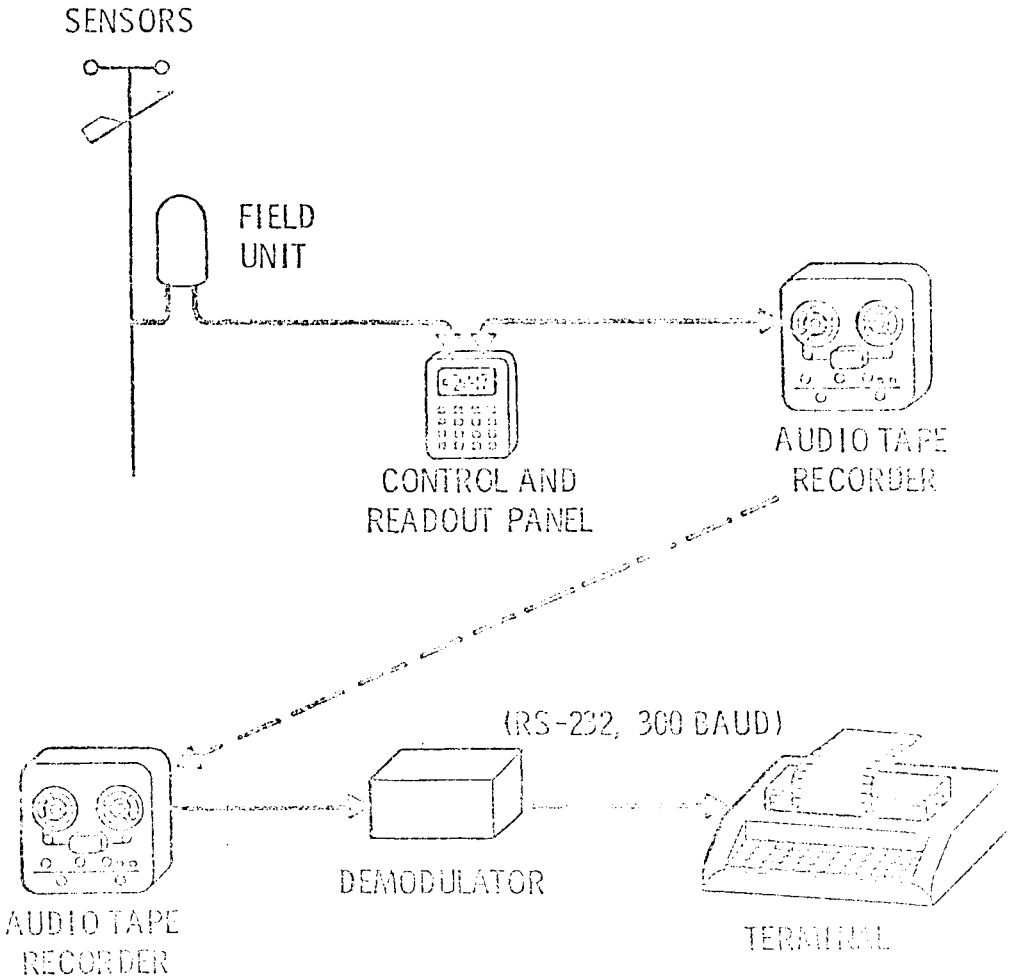
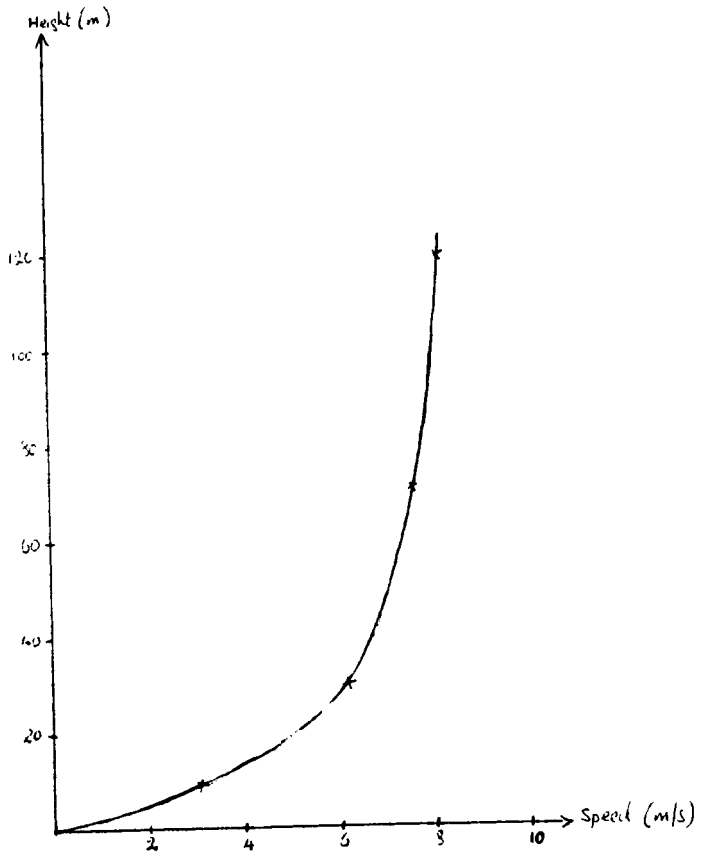


FIGURE 4: Relief map of Mauritius in feet & metres

Shaded areas show high wind energy potential.  
Arrows show probable deflection of wind.



FIGURE 5: Wind profile of Bigara





#### **D. BIOMASS CONVERSION**

**PYROLYSIS OF WOODSHAVINGS AND SAWDUST -  
A REVIEW OF THE DEMONSTRATION PROJECT IN GHANA**

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**ABSTRACT**

A demonstration pyrolytic conversion plant which produces oil, char and combustible gases from sawdust and woodshavings has been in operation in Ghana since 1980. The paper reviews the experiences and the general results of the project.

**INTRODUCTION**

The development and application of local renewable energy resources is becoming increasingly important in several developing countries. As the economy of Ghana is largely based on agriculture and forestry, there is great potential for using biomass as a renewable source of energy for both domestic and industrial applications.

Agricultural and forestry wastes, for example sawdust, rice straw and husks and oil palm wastes, which have high potential for collection for energy conversion, are shown in Table 1 (Chiang et al, 1976). Sawdust, in particular, is produced in large quantities by several sawmills in the Kumasi area and a few other towns in the forest zone. Its disposal often presents problems.

Most of these waste materials may be converted into alternative liquid, solid or gaseous fuels for use in existing domestic stoves, industrial kilns and, in some cases, in engines. One such conversion process is pyrolysis; the thermal decomposition of organic materials.

A pyrolytic conversion plant was set up in 1980 in Kumasi, Ghana, to demonstrate the feasibility of pyrolysis of organic wastes as an economic energy conversion process in Ghana and other developing countries. The plant currently produces char or powdered charcoal, oil, and combustible gases from sawdust and woodshavings. It was located near the demonstration brick factory of the Building and Road Research Institute with the primary aim of providing alternative fuel oil for the brick kiln.

**PROJECT DESCRIPTION**

**Project funding and plant fabrication**

The Pyrolytic Conversion Demonstration Plant, administered by the Building and Road Research Institute (BRRRI), was set up with funds provided by the Bank of Ghana and the United States Agency for International Development (USAID). Some previous work on pyrolysis had been done in the USA by the Georgia Institute of Technology (GIT) (Knight *et al*, 1974). The Building and Road Research Institute (BRRRI) made a request to the USAID for assistance to set up the Demonstration Plant as part of the research and development effort to find alternative fuel oil for brick kilns.

Feasibility studies were conducted jointly by personnel from GIT, BRRI and the Technology Consultancy Centre (TCC) of the University of Science and Technology, Ghana. It was recommended that a six-tonne per day labour-intensive pyrolysis plant be set up. Using basic designs provided by the Georgia Institute of Technology, TCC in collaboration with the BRRI and visiting engineers from the GIT, fabricated a prototype pyrolytic reactor and tested it, using sawdust as feed. Following design modifications, four pyrolytic reactors and ancillary equipment were fabricated locally, installed and commissioned. The only items which had to be imported were gas blowers, measuring instruments and an electric transformer.

### **The pyrolysis process and plant**

Pyrolysis essentially involves the thermal decomposition of an organic material in the absence of air to produce charcoal and gases, part of which may be condensed to recover some oil. Figure 1 shows a simple flow diagram of the pyrolytic conversion process.

The demonstration plant consists of four cylindrical steel reactors and two feed dryers. Each reactor is fitted with a process air blower, condenser, demister, gas suction fan, thermocouples and pressure gauges. A mixture of sawdust and woodshavings are dried in the dryer and fed manually at regular intervals into the reactors. The process air blower supplies limited quantities of air for combustion of the bottom part of the reactor charge, to provide the heat for the pyrolysis of the remaining charge. Each reactor is equipped with a manual-operated agitator which is periodically turned to remove cavities in the reactor contents.

Powdered charcoal or char is collected into barrels beneath the reactor whilst the oil is drained at regular intervals from the condenser and demister. The incondensable gases are burned to provide heat for the feed dryers. The feed dryer is the fixed-bed type where the sawdust and woodshavings are piled on a perforated plate below which hot gases are passed to rise through the bed.

The temperature of the gas stream at the inlet of the condenser generally provides a good indication of the pyrolysis conditions inside the reactor. During plant operation, this temperature is monitored and manual adjustments of the process air flow valve are made to maintain it within the recommended range of 120-180°C.

## **PROJECT RESULTS**

### **Plant performance**

The design capacity of the demonstration plant is six tonne sawdust per 3-shift day or four tonne per 2-shift day, with oil and powdered charcoal yields of 18 and 25% (based on dry weight of feed) respectively (Malvar *et al*, 1960). To date the best performance of the plant is the conversion of 2.6 tonnes of dry woodshavings in a 2-shift day to produce 260 litres of oil and 320 kg of powdered charcoal (Hagan, 1982). The oil and powdered charcoal yields range from 6 to 13%, depending on the moisture content of the feed and how efficiently the reactor temperature is controlled.

The generally low yields of the oil and powdered charcoal may be attributed to inefficiencies in drying of the sawdust and manual process control. It has been

recommended that for high oil yields the moisture content of the feed should be 10% or less. But the fixed bed dryer has proved unsuitable for drying of sawdust because the fine nature of the sawdust restricts the free passage of hot gases. Woodshavings have been dried satisfactorily in the dryer, and so currently the reactor feed consists mainly of woodshavings with some small amounts of sawdust. However, woodshavings are produced by only a few wood factories and are not as readily available in large quantities as sawdust. There is therefore a great need for the dryer to be modified to improve the drying of sawdust.

While located near a potential user, the BRRI brick factory, the plant is over 7 km from the nearest source of woodshavings or sawdust. Transport problems have caused irregularities in the supply of plant feed and increased the costs of a hitherto cheap or relatively free waste material.

The combination of inefficient feed drying, irregular supply of wet feed, low product yields and lack of funds for major repairs have made it impossible for the plant to produce sufficient quantities of the pyrolytic oil for utilisation by the brick factory.

### **Application of products**

#### **Pyrolytic oil**

Some of the properties of pyrolytic oil are compared with those of heavy fuel oil in Table 2 (Hagan, 1982). The generally low oil yields, its acidic and tarry nature, lower calorific value and higher flash point, do not suggest that the pyrolytic oil will compete favourably with petroleum fuel oils. Its tarry and acidic properties, in particular, make it unsuitable for conventional oil burners and necessitate the use of expensive corrosion resistant storage tanks.

However, the pyrolytic oil has very good prospects as an alternative wood preservative. In preliminary field tests by Dinsey (1982), two types of pyrolytic oil, a dense type and a lighter one were compared with dieldrin, a standard termiticide. Wood blocks were treated by the immersion method and exposed to subterranean termites and fungi for nine months. Blocks were inspected at three month intervals, and mean percentage weight loss of the blocks caused by the attack are presented in Table 3.

The tests indicated no significant differences between the levels of protection against termite and fungal attack offered by the dense pyrolytic oil and 0.5% dieldrin. Further field tests are in progress.

Detailed chemical analysis of the pyrolytic oil are yet to be undertaken, but the analysis of similar products by Adamezak (1973) indicated that the dense pyrolytic oil may consist of phenols, carbonic acids, tar-oils and tar-coke. Currently most of the pyrolytic oil from the demonstration plant is sold as wood preservative at ₵ 22.00 (US \$ 0.45) a litre. Considering its calorific value the oil may not be easily marketed as fuel at more than US\$ 0.20 a litre.

#### **Powdered charcoal**

Powdered charcoal has been tested for domestic cooking in an adapted sawdust stove (Figure 2). The calorific value of the powdered charcoal is 23,500 kJ/kg, compared with 25,000 kJ/kg for ordinary charcoal. However in comparison with the conventional charcoal stove in Ghana, called "coal pot", the heat efficiency

of the powdered charcoal stove was much lower. Further design modifications need to be made.

The powdered charcoal has been successfully converted to briquettes using cassava starch, pyrolytic oil or natural gums (from a tropical tree, Acacia senegal) as binders. These had satisfactory burning properties, high compressive strength and considerable resistance to abrasion and to shatter when dropped from a height. The briquettes made with cassava starch seemed most suitable for domestic cooking, the other binders producing a lot of smoke and an unpleasant odour during burning. Some of the properties of the charcoal briquettes made with cassava starch as binder are compared with those of ordinary charcoal in Table 4 (Hagan, 1982).

The briquettes made with pyrolytic oil or tree gum, however, have potential industrial application by direct combustion in lime kilns and steel furnaces, or by gasification to generate producer gas. The producer gas may be used directly in industrial kilns or as alternative fuel for stationary engines, for example, for water pumping and electricity generation. Preliminary gasification tests of briquettes made with pyrolytic oil and of ordinary charcoal have been done in a locally fabricated down-draught gasifier (Hagan, 1985). The composition of the producer gas from the two types of charcoal are shown in Table 5, in comparison with typical values for gas from charcoal as reported in the literature (Kjellstrom, 1980). Other results from the preliminary tests are summarised in Table 6.

The calorific value of the gas produced from the charcoal briquettes is comparable to that of the gas from ordinary charcoal. Both values were, however, lower than the typical value of 4.1 MJ/Nm<sup>3</sup> for charcoal reported by Kjellstrom (1980). This may be attributed to the low carbon monoxide and higher carbon dioxide contents of the gas in the preliminary tests. It may be possible to upgrade the calorific value of the gas by finding the optimum balance of air and fuels flow and the most suitable physical size of the briquettes.

The lower calorific value of the gas, certain gasifier design factors and the fuel quality may account for the rather low overall efficiency of the gasifier, compared with the typical gasifier efficiency of 70% reported by Kjellstrom (1980). However, there is some scope for improving the gasifier performance, for example, by modifications of the hearth and grate zones. The gasifier tests were only preliminary and further tests are required to demonstrate the real potential of charcoal briquettes for the generation of producer gas of satisfactory quality.

### **Project administration**

A preliminary economic analysis by Hagan (1982) indicated that the pyrolytic conversion of sawdust and woodshavings could be profitable if the Demonstration Plant were efficiently managed to operate for a minimum of 300 days per year on 2 shifts (16 hours) each day, and the oil and charcoal sold at market prices. The payback period was projected to be about 3 years and the internal rate of return was 45%.

However, owing to the budget constraints and the administrative set-up of the research institute, it has not been possible to manage the Demonstration Plant to be self-sustaining. The plant is frequently shut down as a result of lack of funds for major plant modifications, for example of the feed dryer, for major plant

repairs, and for the ready transport of plant feed and shift workers to the plant site. It has therefore not been possible to demonstrate the economic viability of the pyrolysis of sawdust, which could have enhanced the dissemination of the technology.

The administration of demonstration projects of this nature should involve potential commercial users, for example large private brick factories, or some other industrial interest group, for example, sawmills. These bodies could assist in the provision of funds and profitable management of the plant, whilst the research institute provides the technical skills for monitoring the plant performance and for necessary design modifications.

### **CONCLUSIONS**

Considering the foregoing results and observations of the Pyrolytic Conversion Demonstration Project, the following conclusions are made:

- i. The concept that the pyrolytic oil is the most important product of pyrolysis as an alternative industrial fuel may have to be revised, since its properties may not enhance ready competition with commercial petroleum fuel oils. More emphasis may have to be accorded to charcoal which may be briquetted with part of the pyrolytic oil. The briquettes may be gasified to generate producer gas for industrial kilns and furnaces, or used directly for the same purposes by direct combustion. Further gasifier experiments are needed to establish the gasification of the briquettes as an economical energy conversion process.
- ii. It would seem more practical and economical to market the pyrolytic oil primarily as a wood preservative. It is therefore necessary to undertake laboratory analysis of the oil to identify its significant constituents, and also to explore other possible applications.
- iii. Some aspects of the manual operation of the plant need to be reviewed to ensure higher product yields and quality, and uninterrupted production. In this regard, certain vital operations of the plant should be mechanised. These include the reactor charging and charge agitation. For better control of reactor temperatures, a modest automatic system for the control of air/feed ratio may be worthwhile.
- iv. The pyrolytic conversion of sawdust could be profitable if the plant is managed on a commercial basis, with the products being sold at market prices and with funds readily available for plant repairs and supply of raw materials. In this effort, a sawmill or a wood preservative marketing company, who are potential users of the pyrolysis technology, may be requested to participate in the demonstration project.

### **Future work**

The following activities are to be undertaken on the Pyrolytic Conversion Demonstration Project:

- i. Serious effort to increase product yields through better process control and necessary plant modifications.
- ii. Further studies on charcoal briquetting and gasification.

- iii. Laboratory analysis of the pyrolytic oil to identify important constituents and other possible uses.
- iv. Laboratory pyrolysis experiments on waste from different Ghanaian woods and other agricultural wastes.
- v. Further development work on the powdered charcoal stove.

### ACKNOWLEDGEMENTS

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**TABLE 1: Availability of Forestry and Agricultural Wastes in Ghana**

<b>Waste material</b>	<b>Quantity generated tonnes/year</b>	<b>Major sources in Ghana (regions)</b>
Reforestation waste	1,000,000	All nine regions
Coconut waste	686,000	Western Central
Rice straw and husks	517,700	Northern, Upper
Logging waste	403,000	Western, Ashanti, Brong-Ahafo
Sawdust	25,500	Western, Eastern, Ashanti, Brong-Ahafo
Oil palm waste	23,000	Western, Eastern

**TABLE 2: Comparison of pyrolytic oil with heavy fuel oil**

<b>Property</b>	<b>Pyrolytic Oil</b>	<b>Heavy Fuel Oil</b>
Calorific value (kJ/kg)	23,900	41,000
Flash point (°C)	104	66
Specific gravity	1.19	0.94

**TABLE 3: Mean percentage weight loss of treated wood blocks  
exposed to termites and fungi**

<b>Treatment</b>	<b>% Weight loss of blocks</b>		
	<b>3 months exposure</b>	<b>6 months exposure</b>	<b>9 months exposure</b>
Dense pyrolytic oil	7.7	9.8	16.8
Light pyrolytic oil	6.7	25.6	55.5
0.5% dieldrin solution	5.7	8.4	17.1
Untreated	20.6	61.9	89.8

**TABLE 4: Properties of charcoal briquettes  
(with cassava starch as binder) compared with ordinary charcoal**

Property	Charcoal briquettes	Ordinary charcoal
% pure carbon content	90	95
% volatile matter	1.0	0.7
% ash content	10.0	4.7
% moisture content	3.4	0.2
Compressive strength, mPa	2.3	3.7

**TABLE 5: Composition of producer gas from charcoal briquettes  
and ordinary charcoal**

	Gas composition from briquettes %	Gas composition from ordinary charcoal %	Typical gas composition from charcoal (from literature) %
CO <sub>2</sub>	4.0	6.0	3.0
CO	17.8	16.6	28.7
H <sub>2</sub>	1.6	3.8	3.8
CH <sub>4</sub>	1.6	1.2	0.2

**TABLE 6: Summary of gasifier test results**

	Gasification of charcoal briquettes	Gasification of ordinary charcoal
Average feeding rate, kg/hr	10.4	8.4
Average gas discharge rate, Nm <sup>3</sup> /min	0.23	0.23
Calorific value of gas, MJ/Nm <sup>3</sup>	2.84	2.83
Rate of energy production, MJ/hr	39.2	39.2
Efficiency of gasifier, %	16	18

FIGURE 1: Flow diagram of pyrolysis system

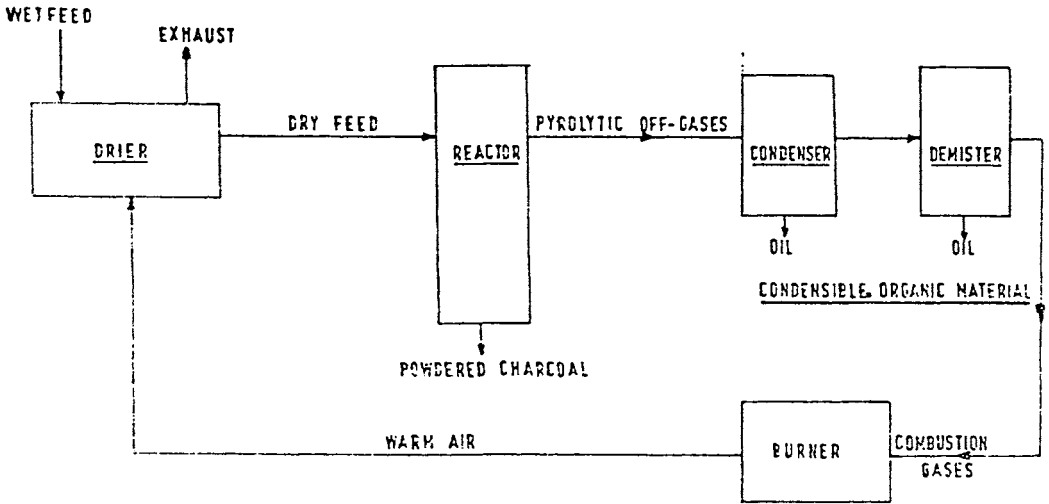
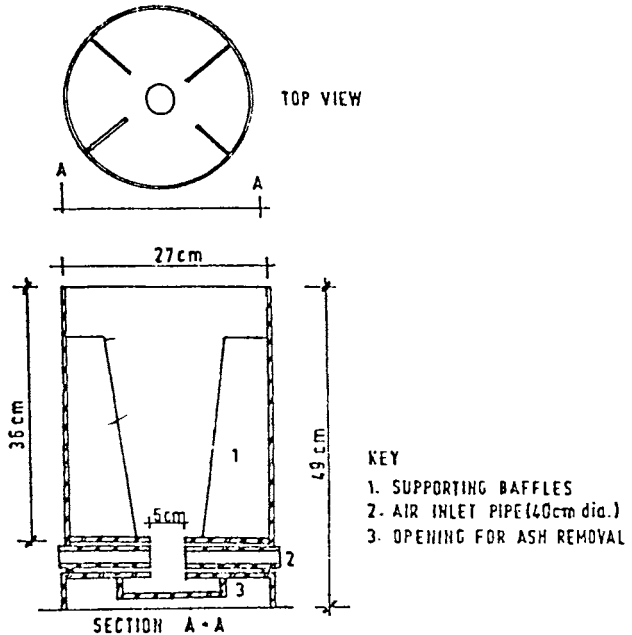


FIGURE 2: Sketch of powdered charcoal stove



## DEVELOPMENT AND TESTING OF OVENS USING SAWDUST AS FUEL

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### ABSTRACT

The development and laboratory testing of a prototype "hole-through - sawdust" type burner and oven is described. Four models of the oven were field tested to obtain socio-economic data on user reaction and its potential for future use. The oven produces temperatures comparable to standard electric and gas settings by appropriate loading of the sawdust burner and can maintain these ranges of temperatures to enable baking to be carried out. In field trials carried out in four homes the oven was generally accepted but efforts must be made to reduce the amount of smoke produced. The oven may be very useful to people who bake cakes at home for daily distribution to institutions. In such applications, there is substantial savings in the cost of fuel, compared to gas and electricity operated ovens. The oven's cost is less than one-fourth the cost of electric and gas ovens.

### INTRODUCTION

Sawdust is one of several alternative sources of renewable energy. Bassey (1980) estimates the amount of sawdust available in Sierra Leone at about 2000 m<sup>3</sup>/month. The calorific value of the fuel depends on the moisture content and the species of tree from which the sawdust is obtained. But a generalised estimate is a calorific value of about 16,000 kJ/kg at a moisture content of about 20% (dry basis), which corresponds to open air drying under local conditions (Bassey 1980).

A method of burning sawdust in "hole-through sawdust burners" has been extensively studied by Bassey (1977, 1983). The purpose of this article is to describe the design, development and testing of two prototype ovens using sawdust as a fuel in "hole-through-sawdust" burners and that practical application in household baking.

### OVEN DESIGN

#### The burner

The burner (Figure 1) consists of a container having a base area 40 x 40 cm<sup>2</sup> and 20 cm high, made of 0.06 cm thick galvanised iron sheet metal. Nine holes, 2 cm in diameter and situated about 10 cm apart in the base of the container serve as the air inlet holes. This configuration was derived from general equations developed by Bassey (1977, 1983), in order to achieve an oven size comparable to existing electric or gas ones and a burning time of more than two hours. The generalised equations for designing burner size are as follows:

$$d/D_B = C_1 \exp(C_2 t) \quad (1)$$

$$m_f/t_H = C_3 \exp(C_4 D_B) \quad (2)$$

where  $m_f$  is mass of sawdust consumed in  $t$  minutes in g;  $d$  and  $D_B$  are burner hole and air inlet hole diameters in cm; and  $C_1, C_2, C_3, C_4$  are constants.

The burner is charged by placing cylindrical rods, with diameters slightly less than  $D_B$ , through the holes and packing the sawdust around them tightly by hand.

The rods are then carefully withdrawn leaving vertical holes through the sawdust which are lit to produce heat. Depending on the amount of heat needed, one to nine burner holes are lit.

### Ovens I and II

Prototype I is shown in Figure 2. It is made from 0.06 cm thick galvanised iron plate with double walls, between which is placed 5 cm thick fibreglass wool insulation. An ash tray is situated below the burner and the door is insulated. The chimney passes through the baking space and exhaust gases also heat up this space. Upper and lower oven spaces are created by a removable shelf made of galvanised iron sheet. To shield the oven space from the burner compartment, an air gap (8 cm thick) sandwiched between two plates was created with a flap opening for air to enter. The chimney is 60 cm long and 8 cm in diameter. Dimensions of the oven space are about 40 x 40 x 30 cm<sup>3</sup>.

Prototype II is identical to prototype I, except that the bottom plate sandwiching the air gap between the burner and oven space was removed. Hot gases thus come into direct contact with the bottom of the plate separating the burner area from the baking space.

### Instrumentation

Chromel-alumel (type K) thermocouples, connected to a thermo electric digital electronic temperature indicator, ELPH 4 model, were located at five points in the oven as shown in Figure 2. During tests the ovens were placed on a scale so as to measure the decrease in mass of the fuel due to combustion.

### EXPERIMENTAL PROCEDURE

The first set of experiments were done using prototype I with 2cm diameter burner air inlet holes. Seven burner holes were packed to a height  $H$ . The whole burner was weighed and the holes were then lit by burning paper or wood shavings in the holes. When the sawdust was glowing uniformly throughout the height of the holes, the burner placed in the oven and the whole equipment weighed.

Temperatures and the weight of the oven were recorded at intervals of between 5 and 15 minutes until the sawdust was completely burned. This was indicated by a temperature drop in the combustion chamber and reduction in smoke from the chimney. In several tests, burner holes were loaded to a height of 8, 10, 12 and 14cm. The damper was usually fully open but some tests were carried out with the damper being 1/2 and 1/8 open.

The above procedure was repeated with oven II. In these experiments, the parameters used were 5 or 7 burner holes,  $D_B=2$  cm and  $H=6, 8, 10, 12$  cm. In each case the damper was fully open.

All the sawdust used during the tests had a moisture content of 23% (dry basis). The density of packing, about  $200 \text{ kg/m}^3$ , was maintained during the experiments.

## **RESULTS AND DISCUSSION**

### **Relative temperatures in Oven I**

The amount of heat transferred from the combustion chamber to the oven space depends on the relative magnitudes of temperatures. Typical temperature variation with time are shown in Figure 3. Hot gases in the burner chamber attain maximum temperatures of around  $300\text{--}320^\circ\text{C}$  and in the oven spaces up to  $150^\circ\text{C}$ . Temperatures are up to  $40^\circ\text{C}$  lower in the burner chamber owing to the metal shelf separating the lower and upper oven spaces. Temperatures in the chimney are generally higher than those in the oven space but drop below the values for the lower oven space as a result of heat losses during the final stages of combustion of the fuel. This indicates the ability of the oven to conserve useful heat in the baking space. Temperatures in the oven door typically range between  $30$  to  $100^\circ\text{C}$  during the operation of the oven.

### **Effect of height of packing on temperatures in Oven I**

Results showing the effects of increasing the height of packing on the temporal variation of temperatures are shown in Figure 1. Combustion chamber temperatures are dependent on the value of  $H$  but the maximum temperature does not exceed  $400^\circ\text{C}$ . Similar trends are observed for the lower oven space temperatures, where working temperatures of between  $150$  and  $160^\circ\text{C}$  are possible after  $40$  to  $180$  minutes depending on the height of packing. During baking it is necessary to maintain a relatively constant temperature and it has been taken that a temperature  $5^\circ\text{C}$  below the maximum of the lower space is a working range of temperatures.

Temperatures in the upper oven space also depend strongly on the value of  $H$  but they are substantially lower. These results indicate that the shelf can be useful for baking foodstuff requiring different temperatures at the same time.

The time taken to reach the maximum range of temperatures are not unrealistic. Oven I has an air space sandwiched between two galvanised iron plates and temperatures in the baking space can be increased by removing the plate immediately above the burner.

### **Consumption of sawdust in oven I**

The amounts of sawdust used in the burner during various tests are shown in Figure 5 for Oven I. The linear variation of  $M_f$  is consistent with results of Bassey (1983). For a burner with  $N=7$ ,  $D_B=2 \text{ cm}$ , Bassey (1983) estimated the consumption to be:  $M_f/H = 2.05 \text{ t}$ . From our results we estimated  $M_f/H = 1.47 \text{ t}$ , or 28% lower than Bassey's estimate for sawdust consumption. This is possible as the oven has more flow resistances causing a slower combustion of the sawdust compared to the open burner used by Bassey (1983), in which the only flow resistance was due to the air inlet,  $D_B$ .

### **Temperature control in oven I**

Setting the air inlet flap fully open, half open or one-eighth open had virtually no effect on the burner and the lower oven space temperatures and the inlet flap does not serve any significant purpose. The nature of the packed bed burner makes it difficult to control its burning rate by using flaps. It is proposed that control of temperatures should be achieved by a variation of H and N.

### **Development of oven II**

Testing of oven I suggested that the galvanised plate between the gap and the burner might not be necessary as the temperatures, both in the combustion chamber and in the oven space, were not excessive. A second oven was therefore constructed and tested as mentioned earlier, with the modifications described above. The flap was left fully open during all tests.

### **Performance of oven II**

Temperatures in oven II are shown in Figure 6 for N=7 and H=6, 10 and 12 cm. These results are similar to those discussed for oven I, the difference being that the temperatures in oven II are higher.

Typical comparisons between the oven temperatures and the amount of fuel used are shown in Figures 7a and b, and in Table 1 for the maximum temperatures.

Temperatures are up to 40°C higher in oven II compared to oven I because the removal of the plate above the burner permits the hot gas to come into direct contact with the base of the oven. Another factor increasing the temperatures in oven II is the slight increase in mass of fuel consumed with time (Figure 7b). The increase in fuel may be due to less restriction in the flow of combustion air as a result of removing the plate above the burner.

Performance data for oven II, similar to those for oven I are shown in Table 2. The maximum temperatures and the times taken to attain them are quite encouraging. There is clearly a possibility of controlling oven temperatures by a combination of H and N.

## **PRACTICAL APPLICATION**

### **Baking temperatures and equivalent settings**

Oven II performs better than oven I and was used in experiments relating the result obtained to real-life baking conditions. By manipulating values for H and N, temperatures equivalent to standard settings of household gas and electric ovens were determined (Table 3).

With the exception of the very cool range of temperatures for which data were not available, combinations of H and N could produce working temperatures equivalent to those in gas and electric ovens.

### **Use of oven II for baking cakes**

Many households use gas to bake cakes on a daily basis for sale in various supermarkets and institutions. Table 4 gives burner configurations corresponding to recommended temperatures for baking a list of cakes.

## FIELD TRIALS OF SAWDUST OVEN

### Method

Four families were given a sawdust oven with several sacks of sawdust. Detailed instructions were given on the operation of the oven and on the adjustment of maximum attainable temperatures by a combination of H and N. The trials were carried out over a two week period at the end of which each participant was requested to complete a questionnaire. Frequent visits were made to the households during the field trial to help with any problems.

The backgrounds of each participant, identified by a number, were as follows:

1. Commercial user; daily baking; used gas oven costing 3000 Leones; had an energy problem; monthly fuel cost 30 Leones.
2. Commercial user; daily baking; used charcoal/wood; wood oven costs Le50; no fuel problem; monthly fuel cost Le32.
3. Domestic user (household of 10); baking once a week; electric oven costing Le3000; energy problem; monthly cost Le10.
4. Commercial; baking once a week; electric oven costing Le3000; energy problem; monthly cost Le15.

### Results

The individuals involved with commercial baking used domestic ovens for baking small cakes and cookies for schools and other institutions. All of the participants used conventional gas or electric ovens except one who used wood in a crude oven consisting of a closed container heated over a three-stone-open-fire stove.

Responses to several questions were:

#### Oven operation

(a)	Is burner difficult to load?	Yes (0);	No (4)
(b)	Does lighting of burner take too long?	Yes (1);	No (3)
(c)	Is operation of oven messy?	Yes (2);	No (2)
(d)	Is smoke excessive?	Yes (4);	No (0)
(e)	Is the ash a problem?	Yes (0);	No (4)

#### Baking time and temperature

(f)	Is warming up time too long	Yes (4);	No (0)
(g)	Does oven cool down too quickly	Yes (0);	No (4)
(h)	Is oven temperature too high	Yes (0);	No (4)
(i)	Is oven temperature too low	Yes (0);	No (4)

### Cake quality

(j)	Does product rise well?	Yes (4);	No (0)
(k)	Does product taste well?	Yes (4);	No (0)
(l)	Does product smell of smoke?	Yes (0);	No (4)
(m)	Did product get burnt?	Yes (4);	No (0)
(n)	Overall are you happy with product?	Yes (3);	No (1)

The oven performed satisfactorily, although there were problems such as excess smoke, and some complaints about the burning of the product which should be investigated further.

Users 1 to 4 made savings of 22, 24, 4 and 9 Leones per month respectively. (The only cost incurred for the sawdust was for transportation.) Participants 1 and 2, doing daily commercial baking made the highest savings. Considering that the estimated cost of the oven is 650 Leones, this appliance has a potential for use in the country. Further attempts should be made to assess the viability of using less expensive construction materials such as bricks, so as to lower the capital cost of the oven.

### CONCLUSIONS

A study has been carried out in which sawdust has been used to produce heat energy in an oven for domestic use. The conclusions which can be made are:

- (a) An oven suitable for use in homes has been developed and fully tested.
- (b) The temperatures which can be obtained in the oven by using combinations of the height of packing and number of holes in the burner, are comparable to those specified for conventional gas and electric cookers.
- (c) Results of field tests indicate that the technical performance of the oven and product quality are acceptable to potential users, but the smoke produced during operation should be reduced.
- (d) The oven costs less than a quarter the price of a gas or electric oven and substantial fuel savings can be made with its use.
- (e) The sawdust oven is a technology which should be encouraged as it has a potential for use in small scale commercial baking.

### ACKNOWLEDGEMENTS

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TABLE 1: Comparison of maximum temperatures for ovens I and II for various operating conditions ( $D_B = 2$  cm,  $N = 7$ )

Height of packing H, cm	Oven	Temperature in Oven			
		$^{\circ}\text{C}$	Tmax Range ( $^{\circ}\text{C}$ )	Time taken to attain, (min)	Time spent in range, (min)
8	I	156	151-156	130	55
	II	176	171-176	95	30
10	I	195	190-195	146	45
	II	213	208-213	100	46
12	I	218	213-218	116	39
	II	250	245-250	135	40

TABLE 2: Maximum temperatures for oven II for various values of height of packing, H( $D_B = 2$  cm)

Height of Packing, H, cm	No of Holes N	Temperature in Oven			
		$^{\circ}\text{C}$	Tmax range ( $^{\circ}\text{C}$ )	Time taken to attain, (min)	Time spent in range, (min)
6	5	156	151-156	130	45
6	7	169	164-169	100	35
8	5	162	157-162	100	25
8	7	176	171-176	85	35
10	5	200	195-200	105	40
10	7	213	208-213	73	46
12	5	210	205-210	105	50
12	7	250	245-250	135	40

**TABLE 3: Equivalent temperature settings between gas, electric and sawdust oven II**

Temperature Description	Electric Oven	Gas Thermostat	Oven II	
			H, cm	N
Very cool	110°C/225°F	1/4 - mark		
	120°C/250°F	1/2 - mark		
	140°C/275°F	1 - mark		
Cool	150°C/300°F	1-2 - mark	6	5
Warm	160°C/325°F	3 - mark	8	6
			6	7
Moderate	180°C/350°F	4 - mark	8	7
Fairly hot	190°C/375°F	5 - mark	10	5
	200°C/400°F	6 - mark	10	5
Hot	220°C/425°F	7 - mark	10	7
Very hot	230°C/450°F	8 - mark	12	5
	240°C/475°F	9 - mark	12	7

**TABLE 4: Burner configurations for baking cakes in oven II**

Type of cake	Burner for Oven		Time to wait before baking (min)	Baking time (min)	Comments
	H, (cm)	N			
Plain Cakes;					
Small	10	7	75	15-20	-
Large	8	7	85	25	not recommended for cakes larger than 0.25kg.
Rich Cakes:					
Small	10	5	105	15-20	-
Large (e.g. fruit)	8	7	85	25	not recommended for cakes larger than 0.125 kg.
Sponge Cakes:					
Large	8	7	85	25	"
Sandwich	10	7	75	9-12	-
Biscuits/ Cookies	8	7	85	25	-

FIGURE 1: Schematic diagram of the hole-through-sawdust type burner with a single hole

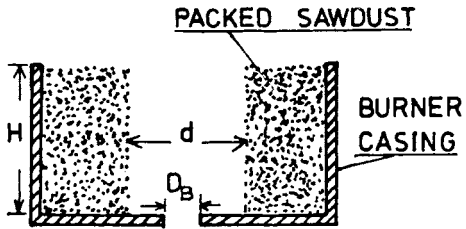


FIGURE 2: Cross-sectional view of oven I showing relative dimensions and location of thermocouples

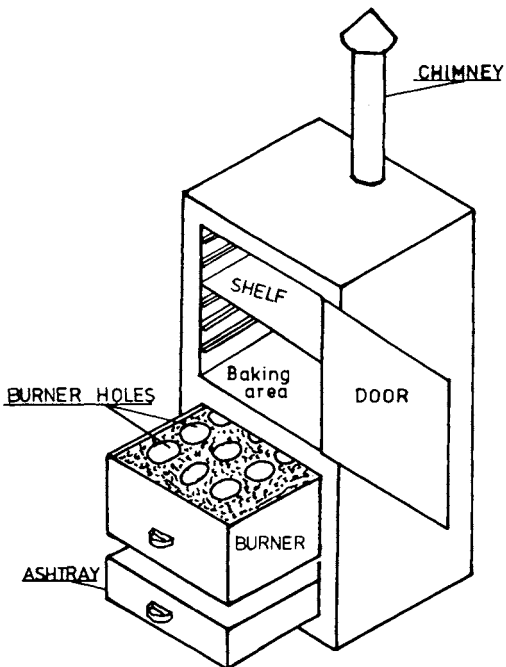


FIGURE 3: Cross sectional view of oven I

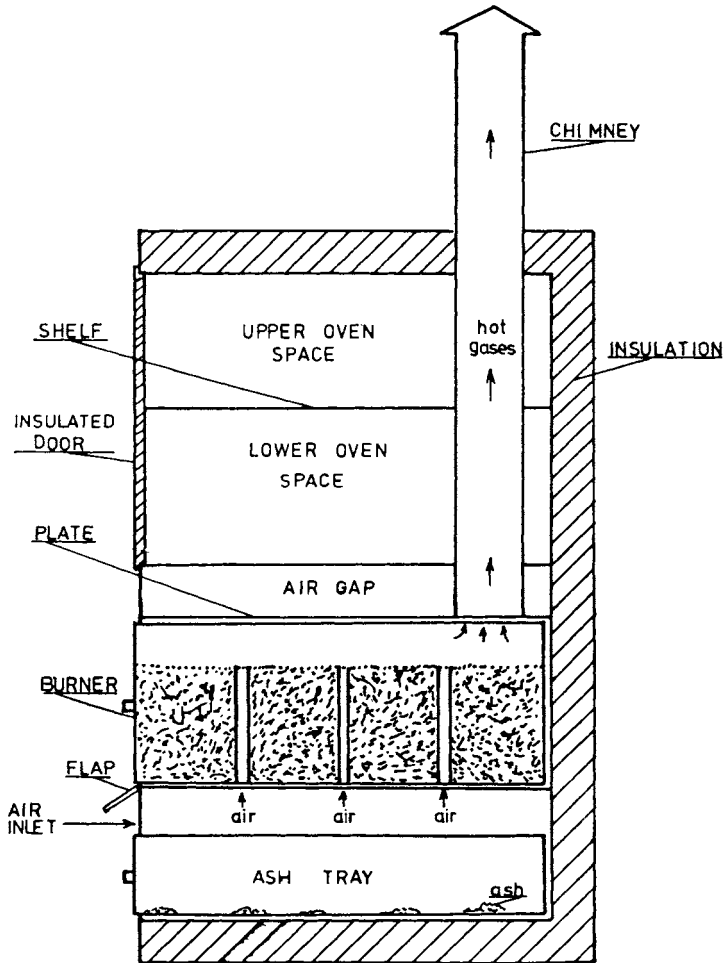


FIGURE 4: Diagram of oven I showing relative dimensions

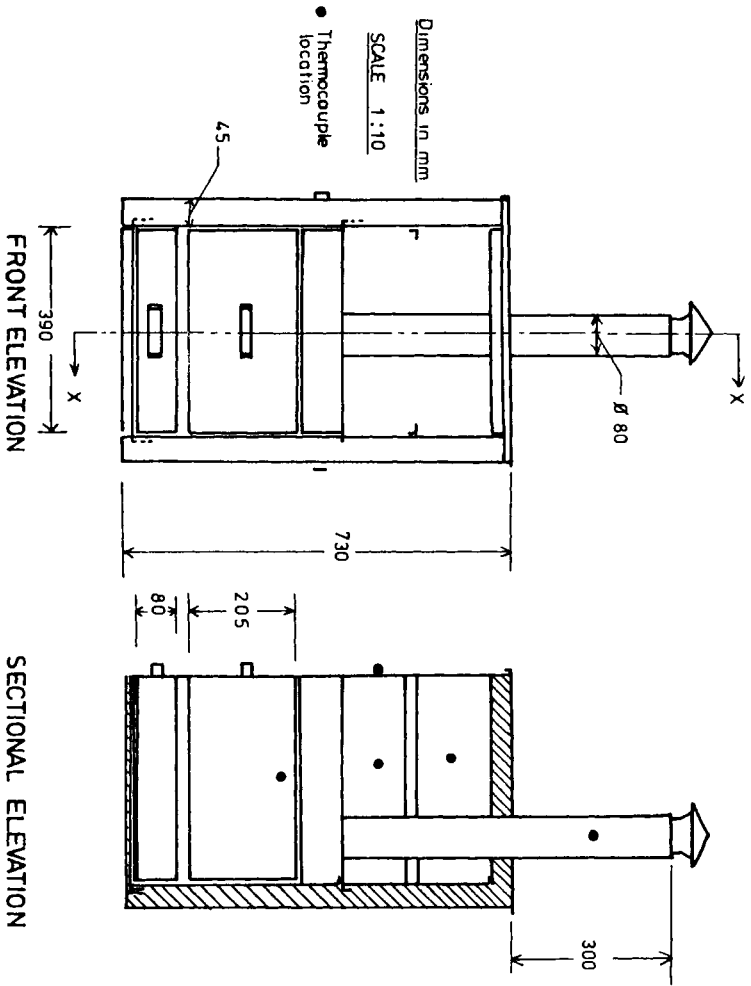


FIGURE 5: Variation of mass of sawdust used with time for oven I

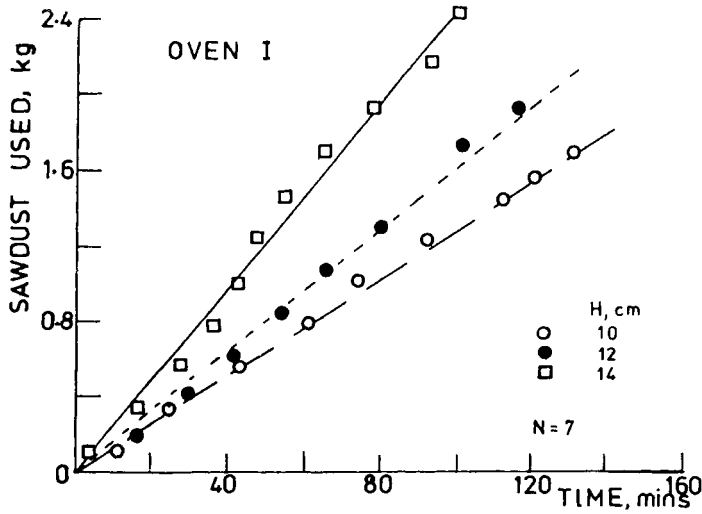


FIGURE 6: Effect of increasing sawdust packing height on the temperature in oven II

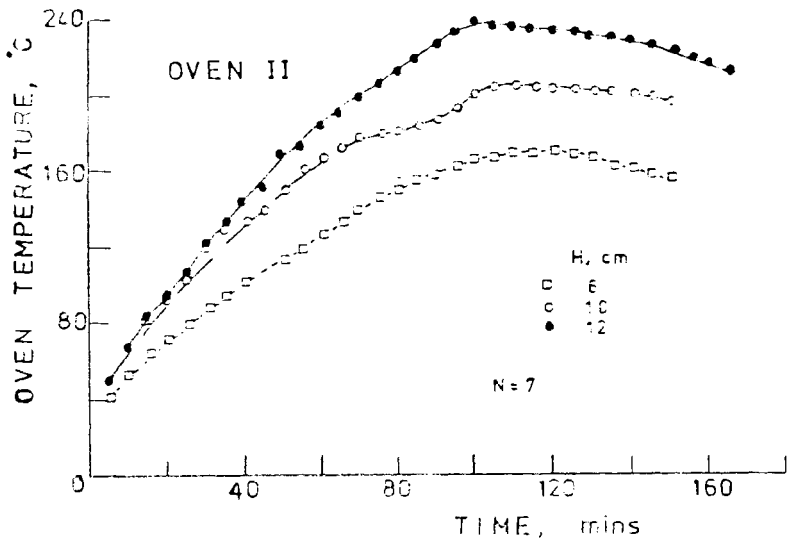
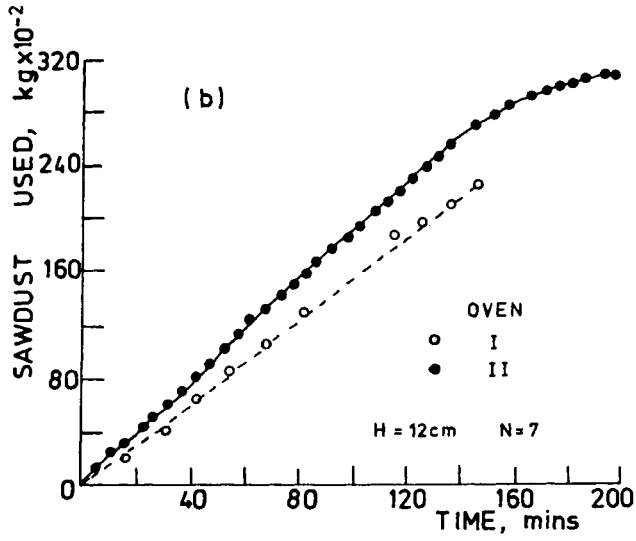


FIGURE 7: Comparison between (a) temperatures in ovens I and II and  
(b) sawdust use over time



## **THE SUITABILITY OF EUCALYPTUS SAWMILLING AND LOGGING WASTES FOR CHARCOAL IN ZAMBIA**

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### **ABSTRACT**

The use of logging, thinning and other types of wastes from large-scale industrial plantations of *Eucalyptus grandis* and *E. cloeziana* for charcoal production is discussed. Charcoaling experiments were carried out using a portable metal kiln and a small rectangular brick kiln using Eucalyptus waste wood in the form of roundwood and slabwood. Average yields were 21.4% for the brick kiln and 19.7% for the steel kiln. The absolute yields from the steel kiln, however, were considerably lower when using slabwood than roundwood. The ash content of charcoal was very low 1-2%, volatile matter content 15-25%, carbon content 70% and bulk density 160 kg/m<sup>3</sup>, on average. The bulk density was a little lower than that for charcoal from indigenous species (220 kg/m<sup>3</sup>). A preliminary survey indicated that it is general acceptability to domestic users.

### **INTRODUCTION**

In Zambia, fuelwood and charcoal production accounts for 85% of the total wood consumption. It is estimated that 75% of the total population (5.48 million in 1980) rely on energy from wood for domestic cooking and heating (Brown, 1980). Wood is preferred to other fuels because it is readily available often at minimal cost except for the collection time. Charcoal as opposed to firewood is most popular among the low- and medium-income groups in urban areas of Zambia. It has been estimated that about 88% of urban households in Zambia use fuel in the form of charcoal (Weerakoon, 1982).

Nearly all the charcoal is produced from the indigenous forest resources. Indigenous species are mixed and referred to as "indigenous charcoal". Charcoal burners are allocated coupes (6 ha of forest) by the Forest Department at a fee of K6 (K1 = 0.483 US Dollars, February 1985) per m<sup>3</sup> of wood extracted. Other sources of raw material for charcoal burners include tsetse fly control cutting areas (approximately 20,000 m<sup>3</sup> were cut in 1980), agricultural clearing areas and industrial forest plantations, which involves 3500 ha of indigenous forest being cleared every year (FAO, 1981). All charcoal in Zambia is produced by traditional earth-clamp kilns using the stack method. It is estimated that at least 435,000 t of charcoal were produced in Zambia in 1983 (Manacas, 1984). The worth of this charcoal to consumers was estimated to be K87 million.

Studies are in progress to reduce dependence on indigenous species for charcoal production and to include logging and sawmilling wastes (Musonda, 1984).

### **MATERIALS AND METHODS**

#### **Raw material**

Charcoaling experiments were carried out to test the use of logging and sawmilling wastes in charcoal production. The species investigated were *Eucalyptus grandis* and *E. cloeziana*, either as single species or mixed together in the proportion of 1:1. The latter is referred to as "Eucalyptus charcoal". The

wood density of *E. grandis* and *E. cloeziana* are estimated at 470 kg/m<sup>3</sup> and 790 kg/m<sup>3</sup> (dry weight basis) respectively.

The logging wastes included first thinnings and other logs discarded at sawmilling because of either deformity or badly attacked by insects and fungi. These were cross-cut into billets of 0.5 m and 1 m lengths. The diameters of the billets ranged from 5 cm to 30 cm. For the sawmill wastes, slabwood was the main material, 2-10 cm thick and 1 m long. The moisture content varied from 15% to 37% (dry weight basis).

### Kilns used

An earth kiln (commonly used throughout the country), a portable steel kiln (steel kiln) and a small rectangular brick kiln (brick kiln) were used. The latter two kilns are of Tropical Institute design.

The billets cross-cut into lengths of 0.5 m and 1 m were used in the steel kiln and brick kiln respectively. For the earth kiln 1 m lengths were used.

Earth kilns are usually built from approximately two cords (4.24 m<sup>3</sup>) of wood covered with earth turf and slowly carbonised.

The steel kiln consists of two interlocking cylindrical sections and a conical cover. The cover is provided with four equally spaced steam release ports which may be closed off with plugs as required. The kiln is supported on eight air inlet/outlet channels, arranged radially around the base. During charring, four smoke stacks are fitted onto alternate air channels (Paddon and Harker, 1980). It has a capacity of 7 m<sup>3</sup> of wood.

The brick kiln consists of a brick chamber for carbonising the wood, a smoke hole and a chimney. The chamber has air vents and an entrance which is sealed with bricks as required. The kiln has an earthen floor and a roof made from mild steel sheets. The sheets are suspended from an external wooden framework to prevent them sagging during the operation of the kiln (Paddon and Robinson, 1984). The capacity of the brick kiln is 14 m<sup>3</sup> of wood.

### Carbonisation period and yield

The carbonisation period is the time from ignition to bagging of cooled charcoal. The charcoal yield is determined from the formula:

$$\text{Percentage yield} = \frac{\text{Oven dry weight of charcoal} \times 100}{\text{Oven dry weight of charge}}$$

### Physical properties

#### Bulk density

Charcoal was loosely packed in a wooden container of 1 m<sup>3</sup> capacity and the weight recorded in order to determine the bulk density of the charcoal.

#### Burning and hardness properties of charcoal

Burning properties were tested in a brazier using lumps of charcoal of 2.5m diameter or more. A 500 g sample of charcoal was ignited. After ten minutes

the time taken to boil 200 ml of water was recorded. Fresh pots with the same volume of water were put onto the brazier until it could no longer bring the water to boiling point. The average time taken to bring water to the boil was calculated and charcoal residue was recorded.

To test the hardness of charcoal, fifteen 500g bags of charcoal pieces sufficiently large to be retained on a 2.5cm x 2.5cm wire mesh were dropped from a height of 2m five times. The amount of charcoal retained was recorded as a percentage of the original 500g.

#### Calorific value

The procedure of the International Organisation for Standardisation (ISO) was followed.

#### Chemical properties

The chemical properties that were tested include the ash content, carbon content and volatile matter. Ash was analysed to determine its composition of phosphorus (P); Sulphur (S); Silica (Si) and iron (Fe). The ISO procedures were applied in determining chemical properties.

#### Survey on the use of Eucalyptus charcoal for domestic purposes

Questionnaires were sent to 1000 charcoal users in Kitwe as a preliminary investigation on the acceptability of Eucalyptus charcoal.

#### Indigenous charcoal

For comparison purposes the physical and chemical properties of charcoal made from indigenous species in traditional earth kilns were determined.

### RESULTS AND DISCUSSION

#### Indigenous charcoal

The properties of charcoal from indigenous species are presented in Table 1.

This method of charcoal production has several advantages: the process is labour intensive; it requires no additional equipment except for hand tools, and no foreign exchange; and it is already familiar to a large number of people. But the disadvantages include: low yields (7-10% on dry weight basis); longer carbonisation periods (3-5 weeks) and little or no control on carbonisation. Studies have shown that a 10% increase in moisture content of wood or earth turf lowers charcoal yield by 2%.

#### Eucalyptus charcoal

##### Carbonisation period and yield

The carbonisation periods for the earth kiln was 14 days and for the brick and steel kilns, 3 and 6 days depending on the moisture content of the wood.

Charcoal from the earth kiln was generally contaminated with soil, roots, leaves etc., because the wood raw material is covered in tuff (sods) before lighting for

carbonisation. There was greater loss due to ashing in the earth kiln than the other two, owing to little or no control of aeration during carbonisation. Thus yields in the earth kiln are the lowest. The yields of the three kilns are shown in Table 2.

Eucalyptus cloeziana had the highest percentage yield in all kilns. It is a heavier timber. Slabwood produced better results in the brick kiln than in the other two kilns while logging wastes are better utilised in the steel kiln.

The brick kiln is the most efficient kiln for both logging and sawmilling waste. But for substitution in the present system, the steel kiln is best because of its mobility. The brick kiln however would be suitable for large sawmills.

#### Physical properties

Eucalyptus cloeziana has the highest bulk density of 190 kg/m<sup>3</sup>; the average for E. grandis and mixed was 160 kg/m<sup>3</sup>. This is a little lower than charcoal from indigenous species.

The burning and hardness properties are presented in Table 3. There was little difference in these properties, and all types of charcoal produced would be suitable for domestic and industrial purposes.

The results on calorific value are presented in Table 4. There are marked differences in the heat energies (calorific values) and this may be due to differences in the rate of burning during carbonisation.

#### Chemical properties

The chemical properties are given in Tables 5 and 6.

The chemical properties seem to be comparable and in the range of the requirements of charcoal for industrial use, for example in copper refining. Ash composition is also quite comparable except for silica which is quite high in the case of the earth kiln because of contamination with soil.

#### Survey on the use of Eucalyptus charcoal for domestic purpose

The results showed that 65% of the users did not like E. grandis charcoal because it was very light and burnt too quickly. Eucalyptus cloeziana and mixed Eucalyptus charcoal were more favourably received and 70% of users felt it could be substituted for indigenous charcoal.

#### CONCLUSIONS

A greater part of the Zambian population will continue to use firewood and charcoal for their domestic needs for a long time to come. A potential to increase the use of charcoal in industry exists.

In order to ensure a continued supply of fuelwood in Zambia fast-growing species of Eucalyptus have to be established and the use of logging and sawmill wastes for charcoal production should be encouraged because the properties of this charcoal are as good as charcoal from indigenous species. The survey of charcoal users indicated that Eucalyptus charcoal is generally acceptable.

The present method of charcoal production (by earth clamps) will need to be replaced with more efficient methods such as portable steel kilns and brick kilns. Financial assistance to encourage charcoal burners to employ the net method must be made.

#### ACKNOWLEDGEMENT

I would like to thank Dr G D Pearce, who read through the manuscript and made some helpful suggestions.

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**TABLE 1: Physical and chemical properties of indigenous charcoal produced by earth kilns**

<b>Properties</b>	<b>Values</b>
<u>Physical</u>	
Bulk density	220 kg/m <sup>3</sup>
Hardness assessment	90%
Burning (boiling time)	2.00 min
Calorific value	31,350 KJ/kg
<u>Chemical</u>	
Carbon content	74%
Volatile matter	23%
Ash content	3.0%
Phosphorus	1.5%
Sulphur	0.2%
Silica	1.0%
Iron	1.2%

**TABLE 2: Charcoal yields (%) from earth, steel and brick kilns**

<b>Type of wood</b>	<b>Kiln</b>		
	<b>Earth</b>	<b>Steel</b>	<b>Brick</b>
<b>Logging waste</b>			
<u>E. grandis</u>	7.1	17.5	16.0
<u>E. cloeziana</u>	9.6	20.0	19.4
Mixed	8.5	19.7	18.4
<b>Slabwood</b>			
<u>E. grandis</u>	2.9	10.6	17.4
<u>E. cloeziana</u>	6.0	15.3	29.6
Mixed	4.1	13.9	21.4

TABLE 3: Burning and hardness tests

Type of wood	Kiln	Burning properties			Hardness assessment	
		Boiling time (min)	Residue Weight (g)	%	Weight retained (g)	%
<b><u>Logging waste</u></b>						
<u>E. grandis</u>	Earth	2.94	114	23	338	68
	Steel	2.95	118	24	367	73
	Brick	2.97	121	24	305	61
<u>E. cloeziana</u>	Earth	2.99	127	25	406	81
	Steel	2.90	120	24	400	80
	Brick	2.96	125	25	403	81
Mixed	Earth	2.64	118	24	366	73
	Steel	2.65	111	22	364	73
	Brick	2.67	112	22	365	73
<b><u>Slabwood</u></b>						
<u>E. grandis</u>	Earth	2.80	118	24	340	69
	Steel	2.83	122	24	370	75
	Brick	2.86	128	25	325	62
<u>E. cloeziana</u>	Earth	2.90	112	23	408	83
	Steel	2.93	117	24	400	84
	Brick	2.97	120	23	410	87
Mixed	Earth	2.89	118	24	407	81
	Steel	2.91	126	25	409	82
	Brick	2.93	128	26	410	82

TABLE 4: Calorific value (KJ/kg) of Eucalyptus charcoal

Type of wood	Kiln		
	Earth	Steel	Brick
<b><u>Logging waste</u></b>			
<u>E. grandis</u>	28,440	30,900	30,390
<u>E. cloeziana</u>	28,510	29,470	29,640
Mixed	28,480	29,750	29,900
<b><u>Slabwood</u></b>			
<u>E. grandis</u>	28,000	30,560	30,080
<u>E. cloeziana</u>	28,230	29,060	29,490
Mixed	28,130	29,350	29,260

**TABLE 5: Chemical properties of Eucalyptus charcoal**

Type of wood	Kiln	Chemical properties (%)		
		Ash	Carbon	Volatile matter
<b><u>Logging waste</u></b>				
<u>E. grandis</u>	Earth	1.9	70	21
	Steel	1.6	70	19
	Brick	1.5	72	19
<u>E. cloeziana</u>	Earth	1.8	71	17
	Steel	1.0	70	17
	Brick	1.0	73	15
Mixed	Earth	1.6	69	18
	Steel	1.3	70	15
	Brick	1.2	70	14
<b><u>Slabwood</u></b>				
<u>E. grandis</u>	Earth	2.9	69	27
	Steel	2.5	70	24
	Brick	2.3	71	25
<u>E. cloeziana</u>	Earth	1.7	68	26
	Steel	1.2	70	20
	Brick	1.0	69	18
Mixed	Earth	2.3	70	25
	Steel	1.9	70	22
	Brick	1.6	70	21

**TABLE 6: Ash Composition (%)**

Type of wood	Kiln	P	S	Si	Fe
<b><u>Logging waste</u></b>					
<u>E. grandis</u>	Earth	1.7	1.4	12.4	1.6
	Steel	1.5	3.9	10.6	1.3
	Brick	2.6	1.5	9.3	1.1
<u>E. cloeziana</u>	Earth	1.7	2.6	10.3	2.2
	Steel	3.3	2.1	7.5	1.2
	Brick	3.1	1.9	4.8	1.2
Mixed	Earth	1.7	1.9	10.4	2.0
	Steel	2.6	3.0	9.8	1.2
	Brick	2.9	1.6	8.0	1.1
<b><u>Slabwood</u></b>					
<u>E. grandis</u>	Earth	1.6	1.3	17.0	2.9
	Steel	1.5	3.7	11.3	1.4
	Brick	2.0	1.6	10.5	1.0
<u>E. cloeziana</u>	Earth	1.5	2.3	12.7	3.0
	Steel	1.7	2.9	8.5	1.3
	Brick	2.9	1.7	6.1	1.2
Mixed	Earth	1.6	1.8	15.4	2.9
	Steel	1.7	3.3	9.6	1.2
	Brick	2.1	1.6	7.9	1.1

## **DETERMINATION OF TECHNO-ECONOMIC VIABILITY, RELIABILITY AND DURABILITY OF A CHARCOAL RETORT PROTOTYPE**

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### **ABSTRACT**

The paper briefly describes a charcoal retort model designed to improve efficiency of charcoal production and recovery of by-products. The design is technically sound. However the initial prototype with 4.5 m<sup>3</sup> retort chamber capacity is not economically viable. A 10 m<sup>3</sup> capacity retort chamber increased the profit margin with a corresponding 18% increase in the rate of return on investment. The rate is further increased by 30% if the crude pyroligneous liquor and tar was to be sold to a central processing distillery plant. The reliability and durability of the retort prototype is also reported.

### **INTRODUCTION**

In attempting to improve on the method of production of charcoal, theoretical and experimental work has been undertaken aimed at designing, constructing and testing a charcoal retort model. The model (Yamba 1983) consists of a retort chamber and furnace connected by five stainless steel tubes (Figure 1) and includes a heat exchanger for recovery of by-products in the form of pyroligneous liquor.

The model has been extensively evaluated to establish optimum operating conditions and determine techno-economic viability, reliability and durability. The findings are reported in this paper.

### **TECHNO-ECONOMIC EVALUATION**

The charcoal retort prototype has been extensively tested over more than 3000 hours of actual operation over a period of five years. The model has proved to be technically sound in as far as charcoal production and recovery of by-products is concerned.

Factors affecting the production rate, ie conversion efficiency, include initiation reaction temperature, and carbonisation and stabilisation times (Yamba 1984). Highest conversion efficiency (35%) was achieved at a carbonisation temperature of 350°C, and stabilisation and carbonisation times of 5 and 9 hours respectively. Under these conditions there was a higher recovery of the by-products in the form of pyroligneous liquor and tar.

Data obtained from the design specifications of the retort model constructed, such as steel, refractory bricks, electric motor, etc, were used to determine the total investment requirement of the project. The retort chamber of the retort model was determined as 0.25 m<sup>3</sup>. To arrive at an economically viable project two retort chamber capacities of 4.5 m<sup>3</sup> and 10 m<sup>3</sup> were selected based on dimensional analysis. Since the size of the retort chamber in the former and latter cases increased three and four times respectively to that of the model, the material cost for the retort chamber increased three, nine and 27-fold for the 4.5 m<sup>3</sup> retort chamber capacity, and four, 16 and 64-fold for the 10 m<sup>3</sup> retort chamber capacity per unit metre, mass and volume respectively. The total capital investment also included the cost of construction and assembly of the plant.

The materials required for the construction of the furnace, increased by a quarter, and a half for a 4.5m<sup>3</sup> and 10m<sup>3</sup> capacity respectively. To obtain the required heat for sustaining a continuous operation of nine hours, a blower with twice the capacity of that used in the model was recommended.

Data, such as, amount of waste fuel and electricity consumed, for determining the operating costs was obtained from various tests undertaken on the retort model. The data were then extrapolated to obtain the operating costs required for the 4.5 m<sup>3</sup> and 10 m<sup>3</sup> retort chamber capacities. To determine the total production cost, the cost of maintenance estimated at an average annual rate of 5% of the capital investment and labour were added to the operating costs.

A comparison of the investment and performance in the first year of operation of charcoal retorts of three different capacities is shown on Table 1. This analysis suggests that the prototype model is not economically viable. The situation slightly improves in the 4.5 m<sup>3</sup> retort chamber capacity but only marginally as the rate of investment is only 2.0% and 11.0% from the sales of charcoal alone, and charcoal and the crude by-product respectively. The profit margin increases significantly using a 10m<sup>3</sup> capacity charcoal retort prototype. There is a corresponding increase in the rate of return on investment of 16.2 and 31.7% from the sales of charcoal only, and charcoal and the crude by-product.

Performance can be further improved if a market for the by-products is identified. For this reason, it is recommended that a central distillery be set up for processing the by-products into products such as wood tar, acetic acid, acetone and methyl alcohol.

#### **DETERMINATION OF RELIABILITY AND DURABILITY OF THE CHARCOAL RETORT PROTOTYPE**

To determine reliability and durability of the system, it is important to consider separately its various components: namely retort chamber, furnace, piping, blower assembly and heat exchanger. The criteria for determining the various economic indices of reliability and durability must also be defined.

The most important criterion of reliability is the probability of non-failure, intensity of failure and average down time. For the charcoal prototype, the probability of non-failure can be measured by the probability (P) of non failure of the various identified components as follows:

$$P = P_r P_f P_b P_p P_{he} \quad (1)$$

where P is probability on non-failure of the charcoal prototype; P<sub>r</sub> of retort chamber, P<sub>f</sub> of furnace; P<sub>b</sub> of blower assembly; P<sub>p</sub> of piping system; P<sub>he</sub> of heat exchanger. The most vulnerable of all the components is the furnace which is subjected to high temperatures.

The intensity of failure of the prototype can be defined as the ratio of the number of failures of the whole plant during a given time interval to the average number of failures of its different components as given below.

$$\lambda = \frac{n}{N_{av}\Delta L} \quad (2)$$

where  $\lambda$  is intensity of failures of the plant;  $N_{av}$  is average number of not failed components of the plants;  $\Delta L$  is given operating time interval.

With the help of equation 2, the probability on non-failure can be determined, using the following equation:

$$P = e^{-\lambda L} \quad (3)$$

where e is natural logarithm.

The mean down time ( $T_o$ ) of the prototype can be determined from:

$$T_o = \frac{\sum t_i}{n} \quad (4)$$

where  $t_i$  is average length of time between two consecutive failures in a given operating time, and n is number of failures in a given operating time.

Durability is an economic analysis index which can be used to determine the economic life of the charcoal plant. It largely depends on operating costs for maintenance and repair and its armotisation rate over a given service life. The economic service life can be determined by the minimum point on a graph showing the two losses against operating time.

The service life of the charcoal prototype according to results from the model is estimated at 10 years. The most critical component which has been identified from the intensive testing is the furnace. According to available data, the furnace, in particular the refractory bricks, will have to be replaced approximately once in every two years. Another critical component requiring frequent replacement within the same order of time is the stainless steel furnace hood and its associated piping which are subjected to high thermal stresses.

During the pilot plant commissioning stage, all the various economic indices which have been identified must be determined and monitored.

## **CONCLUSIONS**

The techno-economic evaluation which has been undertaken in this work has shown that the 10 m<sup>3</sup> retort chamber capacity offers the best investment. A pilot plant based on such a capacity must be constructed for further testing and commissioning prior to commercial production of the design.

During desting of the pilot plant, all attempts should be made to collect data for determining the reliability and durability of the pilot plant.

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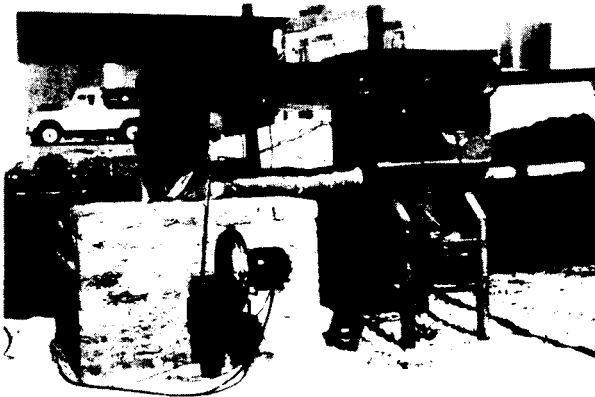
Yamba F D Design and construction of a charcoal retort prototype. Commonwealth Science Council Final Technical Report on the Project Investigation into Charcoal Production.

**TABLE 1: Investment performance in Kwacha at first year of operation of a charcoal retort of three different capacities**

	Capacity (m <sup>3</sup> )		
	0.24	4.5	10.0
Capital requirement	5000	70,000	95,000
Net sales from charcoal only *	1000	24,000	52,000
Net sales from charcoal and by products +	1350	33,000	73,000
Costs (raw material operational cost, overheads, etc)	8000	22,000	30,000
Net profit(loss) before tax +	(-6650)	11,000	43,000
Income tax *	-	600	6600
Income tax +	-	3300	12,900
Net profit(loss) after tax *	-	1400	15,400
Net profit(loss) after tax +	-	7700	30,100
Annual rate on capital *	-	2%	16.2%
Annual rate on capital +	-	11%	31.7%

\* Yamba 1983; + Yamba 1984

**FIGURE 1: Charcoal retort model**



**DESIGN OF A CHIMNEY FOR INCREASING AIR FLOW AND ITS  
EFFECT ON STOVE PERFORMANCE**

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**ABSTRACT**

This paper describes the design of a chimney to increase the air flow and hence improve the thermal heating efficiency and burning rate of stoves. For the purpose of comparing the performance of the earlier designed stoves with the new ones with a chimney, a new parameter "thermal specific fuel consumption" is introduced. Results show that the addition of a chimney stack generally improves stove performance and hence is an important design feature to consider.

**INTRODUCTION**

The performance of charcoal stoves is largely influenced by combustion, heat transfer and boundary layer effect (Yamba). This is further affected by the size of charcoal, control vent, and pre-heating.

Using these efficiency criteria two series of stoves were designed. The first series of stoves are biased to combustion, ie a higher heating efficiency and the second to a higher burning rate but at the expense of a lower heating efficiency. Four sets of stoves have been designed in both series biased to: i. combustion; ii. combustion and heat transfer; iii. combustion and pre-heating; and iv. combustion, pre-heating and heat-transfer. Efficiencies varied from 20-30%. The second range of stoves were similar in design, but the number of 10 mm diameter holes in the grate was increased from 78 to 130.

Eighty such stoves, ie ten of each design have been fabricated and are currently being tested in the field for their acceptability and to determine fuel saving in actual cooking situations in selected households.

A disadvantage of both existing and new designs is the insufficient air flow, resulting in turbulence in the stoves. This is caused by an insufficient air draw from natural convection into the stoves. In attempting to increase the air flow and hence affecting both thermal heating efficiency and burning rate, it was found necessary to design an appropriate chimney. The design of this chimney and its effect on stove performance are described below.

**DESIGN OF THE CHIMNEY**

The height of chimney required chimney ( $H_s$ ) was calculated using the expression developed by Morse as follows (all notations in following equations are given in the appendix):

$$H_s^* = \frac{D_r^*}{D^*} \times 100 \quad (1)$$

$$\text{where } D_{100}^* = K(\rho_a^* - \rho_g^*) - 0.0148 \rho_g^* \frac{(V_g^*)^5}{Q_g^*} \quad (2)$$

The required draft ( $D_r^*$ ) in equation 1 is the sum of all chimney friction, and other losses external to the chimney which includes pressure head losses encountered by air and flue gases in passing at the point of air entry (stove air vent) through the grate air holes, fuel bed in the combustion chamber and chimney duct plus velocity head loss of the flue gases discharging from the chimney. Thus the required draft may be represented by total pressure losses head,  $\Delta H_t$ , which in turn is expressed by the pressure head balance equation as shown below:

$$D_r = \Delta H_t = \Delta h_1 + \Delta h_2 + \Delta h_3 + \Delta h_4 + \Delta h_5 + \Delta h_6 \quad (3)$$

The value of  $\Delta h_1 + \Delta h_2 + \Delta h_3 + \Delta h_4 = \Delta h_s$  has been estimated (Sindano 1983) for a charcoal stove similar in dimensions to the stoves described here.

The chimney friction head,  $h_5$ , was determined using the equation:

$$h_5^* = \frac{78.74 \times f \times H_s \times V_g^2}{g \cdot d_s} \quad (4)$$

The total velocity head loss,  $\Delta h_6$ , according to Morse was determined as:

$$h_6^* = 0.033 \rho_g^* V_g^* \quad (5)$$

The mass of flue gases  $M_g$  leaving per unit time was determined by the expression:

$$\dot{M}_g = \dot{M}_g \times b_f \quad (6)$$

The mass of flue gases  $M_g$  from equation 6 leaving the stove was estimated based on the modified equation required for determining the theoretical amount of air required for complete combustion per kilogram of fuel as follows.

$$M_g = \frac{1}{23} \left( \frac{8}{3} C + 8H - O_r \right) \times \alpha \quad (7)$$

The densities of air and flue gases were determined using the perfect gas law as follows:

$$\rho_a = \frac{P_b}{RT_a} \quad (8)$$

$$\rho_g = \frac{P_b}{RT_g} \quad (9)$$

The preliminary diameter of the chimney was determined using the continuity equation at the pre-determined velocities of 1.5, 3 and 8 m/s which are typical values for flue gases leaving charcoal stoves.

Setting velocity values at 1.5, 3 and 8 m/s the chimney height and diameter were calculated to range from 30 to 70 mm, and 1000 to 2400 mm respectively (Table 1 and 2).

### **TESTING A CHARCOAL STOVE WITH A CHIMNEY**

The charcoal stove used in these series of experiments is similar to the stoves shown in Figure 1 designed to be biased towards greater combustion.

To increase the fluid/wall temperature gradient, ie the rate of heat flow to the pot through increased turbulence, a variable chimney was installed to the stove as shown in Figure 2. Chimney height was adjustable within the range 0-1700mm. The diameter was constant at 75 mm to allow determination of the effect of stack height on thermal performance ie fuel burning rate, heat flow to the pot and thermal efficiency.

In addition to the above parameters of thermal efficiency, a new indicator "Thermal Specific Fuel Consumption" (TSFC) is introduced. This is defined as the ratio of the rate of fuel consumption to the heat flow into the pot as follows:

$$\text{TSFC} = \frac{b_f}{Q_p} \text{ kg fuel/kWh} \quad (10)$$

This indicator is independent of the calorific value of the fuel and gives a complete picture of the behaviour of the amount of fuel used per unit heat flow for a specified period of time. The lower the value of TSFC the more efficiently and economically the system is performing.

Results showing the effect of heating efficiency, burning rate, useful heat flow to the pot and TSFC against stack height are shown in Figures 3-6 respectively. The performance of the two stoves was compared with or without a chimney.

To determine the values of thermal heating efficiency, burning rate, heat flow into the pot and TSFC against chimney height, various parameters such as amount of water heater, rise in water temperature, amount of fuel used, flue gas velocity, burning fuel temperature and flue gases temperature were measured during the experiments.

### **DISCUSSION OF RESULTS**

It can be seen from Figure 3 that heating efficiency increased with an increase in stack height until about 1500mm stack height. Useful heat into the pot (Figure 5) follows the same trend but peaks at 1100mm. TSFC also improves with stack height until 1500 mm. The theoretical optimum stack height was calculated at 1100 mm at a flue gases velocity of 1.5 m/s which is typical of charcoal stoves. This conforms well with experimental findings of an optimum between 1100 and 1500mm. Thus this equation may be useful for determining theoretical optimum heights for different configurations of charcoal stoves including stack diameter.

With a chimney in place thermal heating efficiency ranged from 23.5 to 26% and burning rate and hence useful heat ranged from 0.40 to 0.48 Kg/hr. In the absence of a chimney thermal heating efficiency peaked at 24% and burning rates ranged from 0.30 to 0.35 Kg/hr. Thus, the chimney improves performance, in particular of TSFC. This is indicated by low TSFC values for the stove with

chimney while other values of thermal heating efficiency are quite similar in both systems.

Improved efficiency of the chimney can be attributed to an increase in air and flue gas turbulence which probably improved air/fuel contact and pot wall/flue heat transfer coefficient. Improved air/fuel contact is essential for efficient combustion. A further advantage of the permanent chimney is the time saved during priming of the stoves without a chimney.

### CONCLUSION

The addition of a chimney has been shown to have an important role in improving performance of charcoal stoves. To optimise the design, further work is needed to determine the effect of performance as a function of stack diameter, control vent area, heat transfer and possibly pre-heating.

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**NOTATION**

$b_f$	Burning fuel rate Kg/hr
C	Carbon content %
$D_r$	Required draft $N/m^2$
$D_r^*$	Required draft inches of $H_2O$
$D_{100}$	Available draft $N/m^2$
$D_{100}^*$	Available height per 100 feet of chimney height
$d_s$	Chimney diameter mm
f	Friction wall coefficient
$\Delta H_t$	Total pressure head loss $N/m^2$
$\Delta h_1$	Pressure head loss due to resistance at the stove air vent $N/m^2$
$\Delta h_2$	Pressure head loss through grate air holes $N/m^2$
$\Delta h_3$	Pressure head loss through fuel bed $N/m^2$
$\Delta h_4$	Pressure head loss friction resistance on pot and hood walls $N/m^2$
$\Delta h_5$	Pressure head loss friction resistance on chimney walls $N/m^2$
$\Delta h_5^*$	Pressure head loss chimney walls inches of water
$\Delta h_6$	Pressure head loss total velocity head of flue gases at chimney exit temperature $N/m^2$
$\Delta h_6^*$	Pressure head loss total velocity head of flue gases at chimney exit temperature inches of water
$H_s$	Chimney height mm
H	Hydrogen content %
K	chimney height constant
$M_g$	Mass of flue gases Kg
$M_g^*$	Mass flow rate of flue gases Kg/s
$\Delta P_s$	Summation of pressure head loss due to resistance at the stove air vent, through grate air holes and fuel bed, and due to friction resistance on chimney holes $N/m^2$ ie $h_1 + h_2 + h_3 + h_4$ .
$\Delta P_5$	Chimney friction head $N/m^2$
$\Delta P_6$	Total velocity head loss $N/m^2$

$P_b$	Barometric pressure $N/m^2$
$T_a$	ambient air temperature K(Kelvin)
$T_g$	Flue gas temperature K(Kelvin)
$R$	Gas constant $Kg/KJ K$
$Q_g$	Volumetric flue gas flow rate $m^3/s$
$Q_p$	Heat flow rate kW
$Q_g^*$	Volumetric flue gas flow rate ( $ft^3/s$ )
$V_g$	Flue gas velocity m/s
$V_g^*$	Flue gas velocity ft/s
$\alpha$	Excess air coefficient
$\rho_a$	Density of air $Kg/m^3$
$\rho_a^*$	Density of air $lb/ft^3$
$\rho_g$	Density of flue gases $Kg/m^3$
$\rho_g^*$	Density of flue gases $lb/ft^3$

**TABLE 1: Given values for determination of chimney diameter and height**

$T_a$ (K)	$T_g$ (K)	$P_b$ (mmHg)	$b_f$ (kg/hr)	$f$	$C$ (%)	$H$ (%)	$P_s$ (N/m <sup>2</sup> )	
298	623	660	0.45	2.0	.011	80	10	2.0

**TABLE 2: Calculated chimney height and diameter at three pre-determined flue gases velocities**

Flue gases velocity (m/s)	Chimney dimensions					
	$P_5$ (N/m <sup>2</sup> ) Hs	$P_6$ (N/m <sup>2</sup> )	$D_{100}$ (N/m <sup>2</sup> )	$D_r$ (N/m <sup>2</sup> )	diameter (mm)	height (mm)
1.5	0.343	0.84	113.36 139.7	or 4.55	3.4 or	66 821 1095
3.0	1.326	3.34	51.6 or 201.6	9.79		45 2359
8.0	5.773	27.78	988.79	7.74		29 1864

FIGURE 1: Charcoal stoves used in experiments to determine optimum chimney height



FIGURE 2: Arrangement of test stove showing the stack and hood

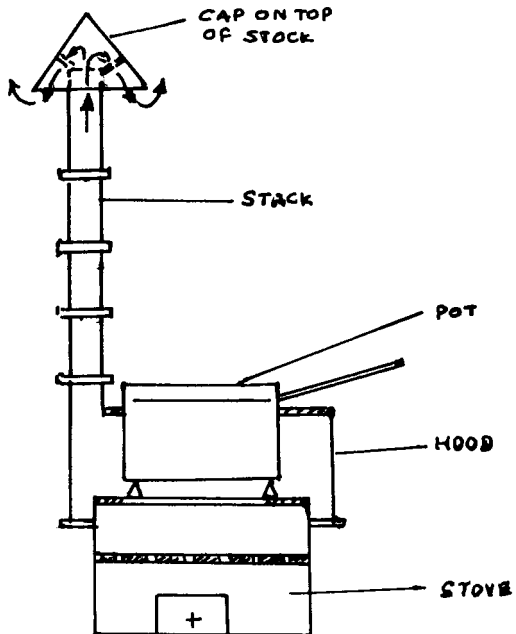


FIGURE 3: Thermal heating efficiency against stack height

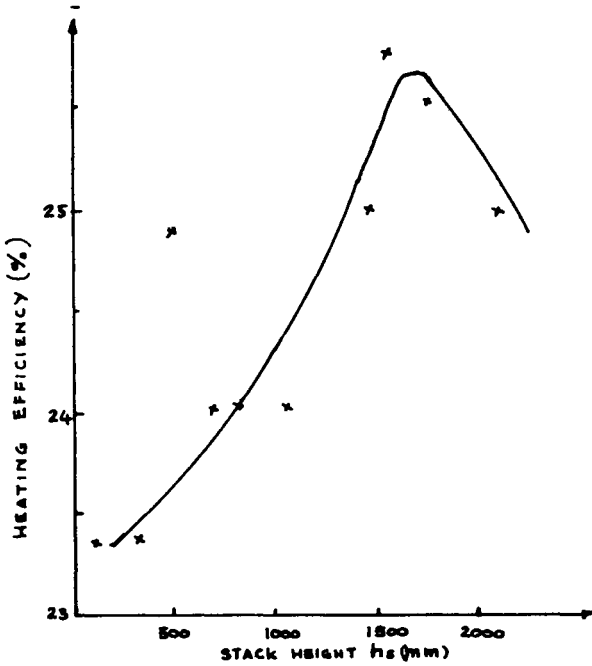


FIGURE 4: Fuel burning rate against stack height

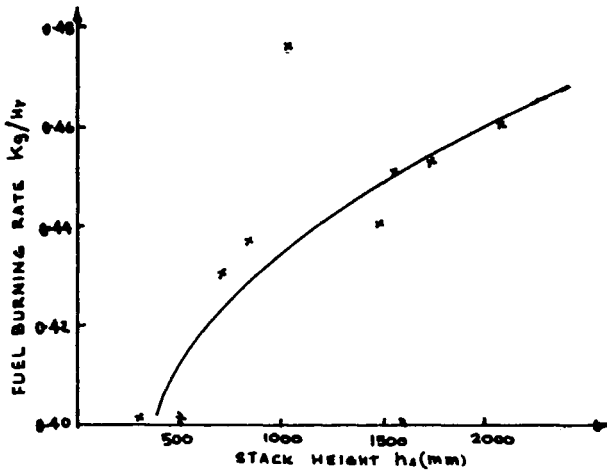


FIGURE 5: Useful heat flow to pot against stack height

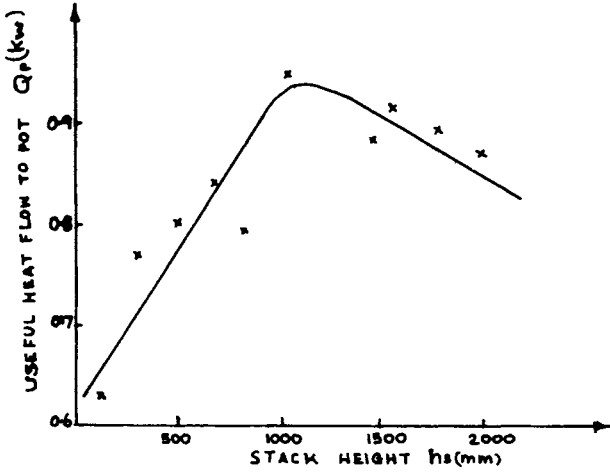
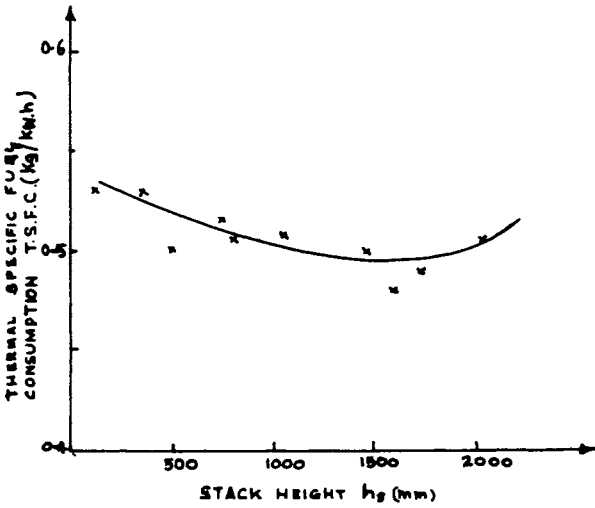


FIGURE 6: Thermal specific fuel consumption against height



**THE DEVELOPMENT, PLANNING AND DISSEMINATION OF  
WOOD/CHARCOAL UTILISING COOKING DEVICES**

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**ABSTRACT**

To ensure meaningful fuelwood conservation, the rural people must be persuaded to abandon the use of fuel-inefficient open hearths which are widely used in the rural areas. The development and diffusion of a fuel efficient woodstove in rural areas is described. The aim of the strategy is not only to familiarise the rural people with a new and beneficial technology but to satisfy national objectives of a. fuelwood/environmental conservation; b. alleviation of felt hardships; and c. employment generation.

**DEVELOPMENT OF EFFICIENT COOKING DEVICES**

The first and important use of wood in rural (communal) areas is as a source of energy for cooking. The traditional open fire has many disadvantages:

1. fire hazards
2. smoke in the home during cooking
3. constant attention of fire during cooking
4. uncontrolled draughts that increase wood consumption
5. cooking at ground level that gives rise to unhygienic cooking conditions.

A rural survey to assess needs in 1980, revealed that rural people were facing acute hardships through fuelwood shortages. Wood collection had increased to well over 10 man-hours per week and household incomes were being diverted to the purchase of fuelwood.

Following the survey, recommendations were presented defining the type of cooking device desired to alleviate hardships. The Department therefore researched into a reasonably priced woodstove that could meet the stated desires for safety, durability and multiple cooking.

**Design features of the stove**

The stove consisted of a metal chimney; a metal grate; a metal damper (for control of draughts through the chimney); a cast iron hot plate (or a hole for a hot water utensil); and a body constructed of fired brick.

**Choice of brick over metal**

Although an earlier survey had shown that metal stoves (mbauras) were fuel-efficient, the brick stoves were seen to have these advantages over metal stoves:-

- i. Cheap to construct in rural areas.
- ii. Retain heat for longer periods of time than metal stoves.
- iii. Bulky but static and therefore safe to use even by children.

The Department of Energy Development therefore improved on a series of Herl-Chulas (Hyderabad 1956) by incorporating a grate, chimney, damper and baffles into the body of the stove for test purposes. Six designs were compared for efficiency of heat utilisation and fuel saving as described below (Seke Woodstove Project, 1982).

#### Determination of heat efficiency

The time and fuel required to evaporate 1 litre of water and the amount of fuel used to bring water to boiling point were recorded. The calorific values of fuel used and moisture content of wood were determined. The efficiency was calculated from the calorific values of heat utilised and calorific value of fuel burnt. The mean of four estimates obtained for each stove was taken as the average efficiency. The equation for determining efficiency is

$$\text{Efficiency of design} = \frac{\text{useful heat used to boil water}}{\text{heat supplied by fuel}}$$

That is,  $\frac{\text{specific heat capacity of water} \times \text{amount of water in vessel} \times \text{temperature rises} + \text{latent heat of steam} \times \text{quantity of water boiled off}}{\text{calorific value of fuel} \times \text{quantity of fuel used}}$ .

The results are as follows:

Stove design	Efficiency (%)
Stove 1 - a brick stove (2 pot holes)	5
Stove 2 - a brick stove (3 pot holes)	18
Stove 3 - modified Nepal Chula (Khatmandu, 1980)	20
Stove 4 - modified smokeless stove (Ghana)	-
Stove 5 - modified Herl-Chula (3 pot holes)	33
Stove 6 - modified Junagadh Chula (Research Action Institute Lucknow 1967) (2 pot holes)	19

### **Conclusion**

Stove 5 had the highest heat utilisation efficiency (33%) and achieved a 30% fuel saving.

### **Charcoal stove**

Although a brick stove was selected for the rural areas, a metal charcoal stove has been designed for use in urban areas. This stove, 'Manyekera', has two pot holes and an air pump to assist the ignition of charcoal. The stove was developed by a private company in Zimbabwe and is marketed through some retail outlets. The efficiency of the stove is 45% but its use at this stage is limited because charcoal is not used widely for cooking in Zimbabwe.

The stove will, however, form part of the charcoal programme initiated by the Energy Department. The programme aims to promote the sale of commercially produced charcoal to urban and peri-urban households as a drive to discourage the use of wood by this sector.

### **EFFICIENCY OF OBJECTIVE ACHIEVEMENT BY ENERGY CONSERVATION PROJECTS**

Efficiency of objective achievement of a project, that is, the extent to which a project converts available scarce resources into objectives or goals, has to be undertaken during the planning of energy projects. These objectives can be divided into either sectoral or national goals, because these distinct parties attach different weights to each of the stated objectives. A project should therefore be implemented as a compromise of the objectives of all sub-systems (rural communities, local authorities and the national government).

### **Resources as part of the objective achievement of projects**

Resource analysis is important since the resources available will control the type and level of activities and hence goals that might be achieved. Resources include

- i. finance
- ii. manpower
- iii. physical site specific resources (land, water, animal waste, etc.)
- iv. implementation capacity (which is an aggregation of all resources that are consumed by the project including the degree of cooperation between various interested parties).

In the field of development or conservation of energy, several projects (biogas, solar devices, afforestation, woodstoves etc) can compete for the available resources. Therefore a ranking order of projects based on relative efficiency of objective achievement is essential. The initial step therefore is to determine goal achievement by a project thus:

Achievement of objective by project using a specific resource(s) =  $\frac{\text{Consumption of resource(s)}}{\text{objective(s)}} = A$

Relative efficiency of objective achievement by project =  $\frac{A}{A \text{ max}}$

where A max is the highest value of A for all given projects.

Objectives can be: i. self-sufficiency in energy (sectoral and national goals); employment generation (sectoral and national); hot water at specified times (sectoral) etc. The ranking of projects is only possible after the calculation of relative efficiency of objective achievement for each project.

#### Cost/benefit analysis

Efficiency of objective achievement can also be measured by undertaking a cost/benefit analysis of each project. In this analysis, it is not useful to use market prices as other costs, for example, use of foreign currency in a project has an economic cost to the nation. Therefore costs of projects, where necessary should be estimated at shadow prices ie scarcity value of components of a projects.

Benefits are usually more difficult to quantitate unless income generation accrues from a project. Social benefits on the other hand can be measured indirectly as gains in other directions.

The present net value of a project arises from the determination of net benefits over a stipulated period of time, ie

$$\frac{\text{Net Benefits}}{\text{time}} = \frac{\text{Benefits} - \text{Costs}}{\text{time}}$$

A project with a high net present value and a high relative efficiency of objective achievement will therefore be the most attractive option. When costs of a project outweigh benefits, this project is said to be economically inefficient.

#### SELECTION OF PROJECTS THAT CONSERVE WOOD

The objective of the Zimbabwean government is to ensure energy conservation particularly of wood. Various strategies to achieve this objective have been attempted and these are:

- a. development of new and renewable energy systems,
- b. rural afforestation,
- c. conservation of wood via the use of wood stoves,
- d. conservation of wood via use of charcoal.

In the area of direct wood conservation, the projects c and d compete for the same scarce resources - manpower, wood and finance. However, as outlined below they do not make equal claims on these resources.

### **Finance**

Because the charcoal project depends on the design and marketing of a metal charcoal stove it is a more expensive option than the wood stove programme which depends on owner-built stoves made out of local materials such as brick, sand and scrap metal.

### **Wood**

Although both projects have a claim on wood, charcoal production is inefficient (25%) use of wood.

### **Manpower**

The charcoal project requires a higher level of demand for manpower for example with marketing skills.

The relative efficiency of objective achievement demands that projects consume scarce resources at a low rate or that they do not place great claims on resources. This would indicate that the woodstove project has a higher objective achievement than the charcoal project.

Thus, although both projects are required for the national objective of wood conservation, the woodstove project has been given a higher priority.

The development of energy systems destined for the rural areas has to take cognisance of the fact that rural areas are economically poor and that adoption of technologies is dependent on the costs of the technologies.

Technologies that require large inputs of initial capital investment are destined to be unacceptable by the rural people. Cost reduction via local production of components may reduce the claim on finance and thus aid adoption.

If a technology, by its nature, has a high claim on a site specific resource, the option to exploit this technology has to be weighed against other competing technologies. In other words, the choice for this technology or project or strategy has to be justified by either cost/benefit or resource analyses. If resources are scarce, implementation capacity of the executing agency becomes low and objective achievement is low.

The woodstove programme in Zimbabwe has therefore been revised to include local production of stove components by local labour to not only reduce the claim on finance available, but to reduce the claim on skilled labour. The establishment of local production units (energy centres) has been incorporated into the woodstove programme.

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## PRODUCTION OF ELECTRICITY FROM BAGASSE IN MAURITIUS

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### ABSTRACT

The problem and potential of electricity production from bagasse is reviewed in the light of the work done by the Sugar Technology Division of the MSIRI on energy balances of sugar factories and on the storage of bagasse. Present energy requirements of sugar factories are analysed and improvements towards energy savings suggested. Boiler performances and bagasse storage problems are also discussed. Examples of excess bagasse potentials are worked out from results obtained and the production of electricity is outlined in connection with excess bagasse handling and storage constraints.

### INTRODUCTION

Bagasse potential as a source of renewable energy has been discussed and analysed at various levels since the first seminar on Energy held at the University of Mauritius in 1977.

There was a National Energy Conference in 1980, a Feasibility Study by Trans Energ in 1982, a Master Plan for the sugar industry in 1984 and most recently a plan of action was announced by the Government. On the production side, power plants at Medine, Mon Desert Mon Tresor and FUEL and a bagasse pelletisation plant at Beau Champ have been installed.

The Mauritius Sugar Industry Research Institute (MSIRI) has directed its efforts to producing accurate data on the energy utilisation of our sugar factories with the object of proposing energy saving measures through plant and operating procedure modifications. It has also studied bagasse conservation problems.

### SUGAR MANUFACTURE

For many years now sugar has been manufactured in Mauritius under conditions which do not require energy saving measures as a surplus of bagasse results in increased expenditure for its disposal.

Boilers and prime movers which have been installed have in many cases relatively low efficiencies, the former consume large amounts of bagasse and the latter large quantities of high pressure steam which are exhausted to meet process house demands. Furthermore, operating procedures are geared to conditions of generous fuel supply, for example the time taken for starting up, shutting down or boiling off are governed more by labour costs than by energy costs.

Measurements of energy flows in a factory have rarely been made. As a result studies on the potential of excess bagasse have had to make several assumptions, or base their calculation on manufacturer's specifications not verified in practice.

### **ENERGY BALANCE SURVEYS**

In 1981, the Sugar Technology Division of the MSIRI ordered equipment for the continuous monitoring of flow rates, pressures and temperatures of steam at the various stages of sugar manufacture. From 1982, factories were surveyed in turn on a round-the-clock basis for periods varying from two to three weeks. Problems were encountered at the beginning and it took some time to assess and implement the techniques of continuous monitoring and logging with electronic equipment.

Energy consumption can now be measured under various factory operating conditions such as start-ups, shut-downs, breakdowns and liquidation. It is also possible to measure fluctuations in demand which are inherent to milling systems and to the process.

There are limitations to what can be achieved for lack of equipment. It is not possible for example to assess boiler performance on a continuous basis as a system for the continuous weighing of bagasse fed to the boilers are not easily available. However, boiler efficiency tests can be carried out for short periods of one to two hours when bagasse weights can be indirectly estimated.

As measurements of flows, pressures and temperatures are taken every 0.5 to 2 minutes, a mass of information is logged and analysed from which a fairly accurate picture of the energy balance of a factory can be drawn.

### **OVERALL ENERGY REQUIREMENT FOR SUGAR MANUFACTURE**

From the 12 factories surveyed so far, a useful comparative assessment of energy required for sugar manufacture has been obtained (Table 1). As boiler and factory performance are not necessarily interdependent, the energy output from the boiler has been related to the factory requirement and expressed in terms of Giga joules/tonne fibre.

Factories in Mauritius operate in two modes:

- a. Generation of surplus electricity for export and process steam make-up.
- b. Live steam throttling for process steam make-up.

In the first mode, it is possible to generate more electricity than is required for process steam if bagasse is available and surplus exhaust is blown-off to the atmosphere. The energy used up in producing this surplus electricity is not considered as a requirement for sugar production. On the other hand, process make-up requirements are dependent on prime mover efficiency, process requirements and the exhaust steam regime and varies from factory to factory. Throttling steam through a turbo alternator can produce electrical energy varying from 25 to 55 Kwh/tonne fibre.

### **Energy saving measures**

Major and expensive modifications will reduce overall energy requirements. In the meantime steps to improve control and balance can and should be taken to reduce unnecessary losses including:

- a. Metering of boiler steam output and condensate return.
- b. Installation of a clarified juice buffer tank to reduce fluctuations in process steam requirements.
- c. In the absence of condensing turbo alternators, export of electricity should be limited to balance process exhaust steam requirements.

### **BOILER PERFORMANCE**

Tests of short duration have indicated a range of boiler efficiencies varying from 50 to 80% of net calorific value. Inadequate excess air control, excessive levels of boiler feed water make-up (up to 40%), incomplete bagasse consumption resulting in high levels of unburnt bagasse in both furnace ash and flue gas are problems that need to be solved. Improvement in this field will require expensive modifications and sophisticated control systems.

### **BAGASSE STORAGE**

Bacterial degradation of bagasse in storage leads to loss of dry matter. The heat released causes loss of moisture and sometimes spontaneous combustion.

Studies on the evolution of these parameters have shown that climatic conditions can lead to losses of up to 25% of dry matter in baled bagasse over 3.5 months, while moisture levels can drop to 20%. The rate of dry matter loss is considerably reduced in bagasse at 25% moisture and below.

Bagasse pellets at 8% moisture keep very well but are expensive to produce. Present research is aimed at drying and densifying bagasse at 25% moisture to achieve a loss of dry matter not exceeding 8% over six months storage.

### **EXCESS BAGASSE POTENTIAL**

Excess bagasse from all factories excluding FUEL, Medine and Mon Tresor which are equipped to use their bagasse for the production of modulated electrical energy, is calculated in Table 2 from the average of results obtained to date.

From the performance of the most efficient unit and after improvement of control and operating procedures the expected potential has been estimated (Table 3).

### **Electricity production**

The production of unmodulated energy will continue and be probably increase if adequate remuneration is obtained for excess bagasse; this production can be estimated to be about 16 GWh with maximum bagasse savings increasing to 35 GWh with more efficient prime movers. From the estimation of present and future excess bagasse availability, the location and sizing of future bagasse-fired power plants can be made with more accuracy. Taking into account the cost of drying and densification on one hand, and the high losses of green bagasse in storage, the immediate use of a maximum amount of loose green bagasse becomes an attractive proposition.

## **CONCLUSION**

The feasibility study on electricity production from bagasse carried out by Trans Energ has shown an annual potential of some 395 GWh. This can now be reviewed and more accurate estimates obtained to determine the number, sizes and location of future bagasse-fired power plants.

The installation of additional measuring and control equipment is of immediate importance as well as the modification of certain operating procedures in sugar manufacturing. Studies on bagasse drying and densification systems must be accelerated to achieve more economical targets.

**TABLE 1: Energy required at boiler outlet for sugar manufacture**

Factory	Nominal Capacity (Tonnes Cane/Hour)	Energy Requirement Giga Joules/tonne fibre
1	115	9.34
2	110	9.62
3	175	10.49
4	115	10.00
5	90	9.82
6	100	10.7-11.5
7	145	9.70
8	70	10.22
9	110	9.6
10	130	9.0
11	90	11.08
12	140	11.2

**TABLE 2: Calculation of excess bagasse**

Cane crushed (Tonnes)		6,250,000
By FUEL, Medine & MDMT 24%		1,500,000
Balance		4,750,000
Actual x S bagasse potential calculated on:-		
Boiler efficiency		70%
Energy required for sugar Manuf.		10.25 GJ/tf
Bagasse consumption other than for actual sugar manufacture		9%
At Fibre % cane	13	16
Excess bagasse available (tonnes)	291,104	358,282

**TABLE 3: Excess bagasse potential after  
process control and operation modifications**

Boiler efficiency		70% NCV
Energy for sugar manufacture		9.0 GJ/tf
Bagasse consumption for weekends etc.		5.0%
At Fibre % cane	13	16
Excess bagasse potential (tonnes)	465,000	572,319

## **CHANGING MODE OF FEEDING FOR IMPROVING THE KVIC DIGESTER**

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### **ABSTRACT**

The performance of batch biogas digester systems has been shown to improve substantially by inoculating fresh cow dung with 14-40 day old starter material. Experiments are reported here to investigate whether similar improvements can be achieved by allowing mixing of spent slurry and fresh material in continuous/semi continuous digester systems. A traditional KVIC digester and an improved design without a partition wall and incorporating a better stirring device are compared. The improved design has 10% higher biogas production. Addition of spent slurry at 2.5% volume does not appear to increase biogas production in semi continuous systems.

### **INTRODUCTION**

Laboratory experiments within the African Energy Programme (AEP) have revealed that using spent slurry would considerably improve batch digester performance by reducing the latent phase period of anaerobic fermentation (Baguant et al 1984; Dhanjee 1984). Starter material 14-40 days old, added at a level of 2.5% by weight to fresh dung feed has been shown to be sufficient to provide the required level of bacterial population for satisfactory biogas production in batch system.

The efficiency of continuous/semi continuous digesters may also be improved by changing the mode of feeding to recirculate spent slurry (starter material). The traditional vertical KVIC model of continuous/semi continuous digester has a partition wall to prevent the short circuiting of fresh material added to the digester, thus ensuring that the retention time chosen for the raw material is achieved. The partition wall prevents the mixing of the fresh material and spent slurry. The initial lag phase in biogas may thus be lengthened while the appropriate bacterial population becomes established within the fresh material.

It is believed that the inlet chamber of the conventional KVIC model digester (Fig. 1) may therefore be acting more or less like a dead space - no allowance being made for any resettling/refloatation: phase separation of materials.

A modified KVIC model digester has been designed to improve its performance. The partition wall has been removed to allow the mixing of the fresh material and the bacterial rich spent slurry. To eliminate short circuiting of fresh material the outlet pipe has been redesigned and the stirrer has been improved.

This paper reports the findings of various experiments to evaluate the performance of this improved digester in comparison with the conventional KVIC model.

### **LABORATORY EVALUATION**

The conventional KVIC digester (Figure 1) has been compared with the performance of an improved biogas digester (Figure 2). The former, digester 1, has an active volume of 206 litres and the latter, digester 2, of 210 litres. In all

test runs, biogas production in digester 1 was corrected to an active volume of 210 litres.

In all cases, the raw material was cow dung fed at a dilution of 1:1 with water. Digesters were operated at room temperature. At the beginning 25% starter material was included. The feeding rate was calculated as follows:

$$\text{Feeding rate} = \frac{\text{Active volume (AV)} \times 7 \text{ days/week}}{\text{Retention time} \times 5 \text{ working days/week}}$$

The gas composition was analysed by flammability tests and gas volume measured in litres by a gas flowmeter.

Two test runs are reported. In the first a retention time of 30 days was used, in the second a retention time of 21.4 days. The first run was forced to end after 8 days because of serious scum formation in the KVIC Digester Design. The layer of scum was 21 cm deep. No scum was formed in the 8 days. The scum breaker/stirrer of both gas holders were improved and utilised in the second run.

In the second run, scumming problems were eliminated. The activities undertaken during the test run can be summarised as follows:

1. 0 - 675.5 (hours since initiating digestion)
  - NO RECYCLING
  - PERIODIC LARGE LOAD (to create gas pressure for burner utilisation)
  - DAILY STIRRING
2. 675.5 - 963.5
  - NO RECYCLING
  - NO LARGE LOAD (GAS FLOW METER in constant operation)
  - DAILY STIRRING
3. 963.5 - 1515.5 (continuation)
  - NO RECYCLING
  - NO LARGE LOAD
  - DAILY STIRRING
  - INTER CHANGE OF GAS FLOW METER to verify results of 1 and 2.
4. 1179.5 - 1515.5 (continuation)
  - As 3 but RECYCLING of 2.5% Starter Material to KVIC Digester Design (MODE OF FEEDING CHANGED)

- IMPROVED DIGESTER DESIGN AS in 3 (MODE OF FEEDING NOT CHANGED)
5. 1419.5 - 1515.5 (continuation)
- KVIC as in 4
  - IMPROVED Digester Design - MODE OF FEEDING changed - Recirculation of 2.5% Starter Material
6. 771.5 - 795.5 and 1155.5 - 1299.5
- 24 hour break in monitoring (due to gas leakage)
  - 6 days break in monitoring (due to gas leakage)

### **Results**

The daily average biogas production for the two designs of semi continuous biogas digester is shown in Figure 3. Biogas production in the improved design is presented as percentage increase or decrease over that of the conventional KVIC design.

Except with large loads, where there was loss of gas from the improved digester, this digester performed better than the KVIC design. Even with interchange of gas flow metres, the improved design performed better.

The digesters are still running, but at time of the last measurements reported here, recirculation of starter material at the level of 2.5% of volume did not appear to change the rate of gas production in the improved design.

The stirring mechanism of the KVIC design was difficult to use owing to scum formation. That of the improved digester, operated very easily.

### **DISCUSSION AND CONCLUSIONS**

1. Recirculation of starter material to a quantity of 2.5% of weight of the fresh cow dung does not seem to affect the performance of the two semi-continuous digesters tested. A longer operating time is necessary to confirm this. It may be that the rate of sedimentation of the slurry is sufficient to inoculate the fresh feed with enough bacteria to start immediate biogas production. In batch system there is no endogenous colony of methanogens.
2. It is not possible to explain the better performance of the improved digester design compared to the conventional KVIC design. However, there may be a more concentrated population of methanogens, since the improved Digester design is an upflow digester with a greater sludge bed volume.
3. No value can yet be given to the efficiency of the improved digester design compared to the conventional KVIC until the systems have been operating for a longer period. However, this will be in the order of a 10% increase in performance under the same conditions. The improved digester design would require a lower initial investment for a given

volume of biogas required, thus bringing the biogas technology within the grasp of even more people.

4. The improved digester design accomodates a high solids concentration and high loading rate without any scum formation problem. Since a lower dilution of the feed is required the design may be of interest since (a) it will require less water and (b) it could treat a large waste volume without requiring a proportionate increase in its sizes, again helping to keep the initial investment cost at a minimum.
5. The design of the improved digester permits the use of a better scum breaker/stirring mechanism. The extra cost of this unit would easily be offset by the saving of not having to build a partition wall as in the KVIC design. A proper comparative economic evaluation may need to be carried out.

#### **ACKNOWLEDGEMENTS**

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FIGURE 1: KVIC design digester

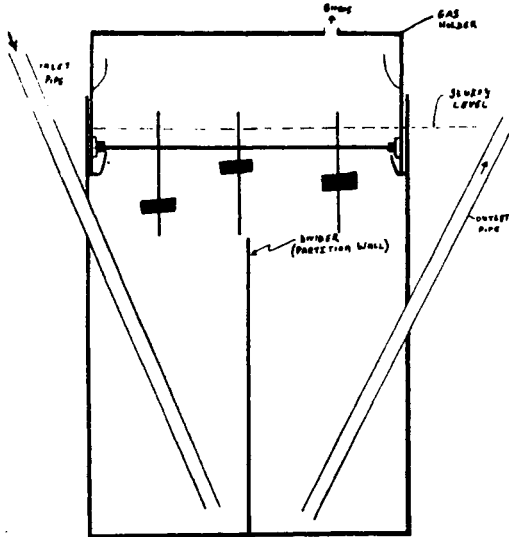
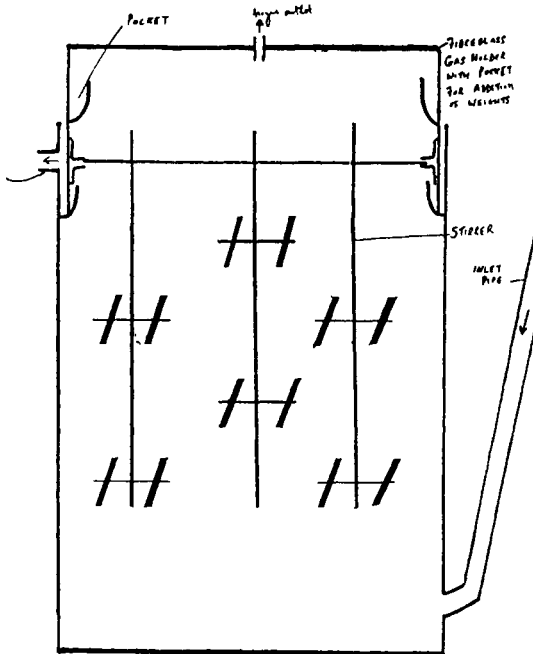
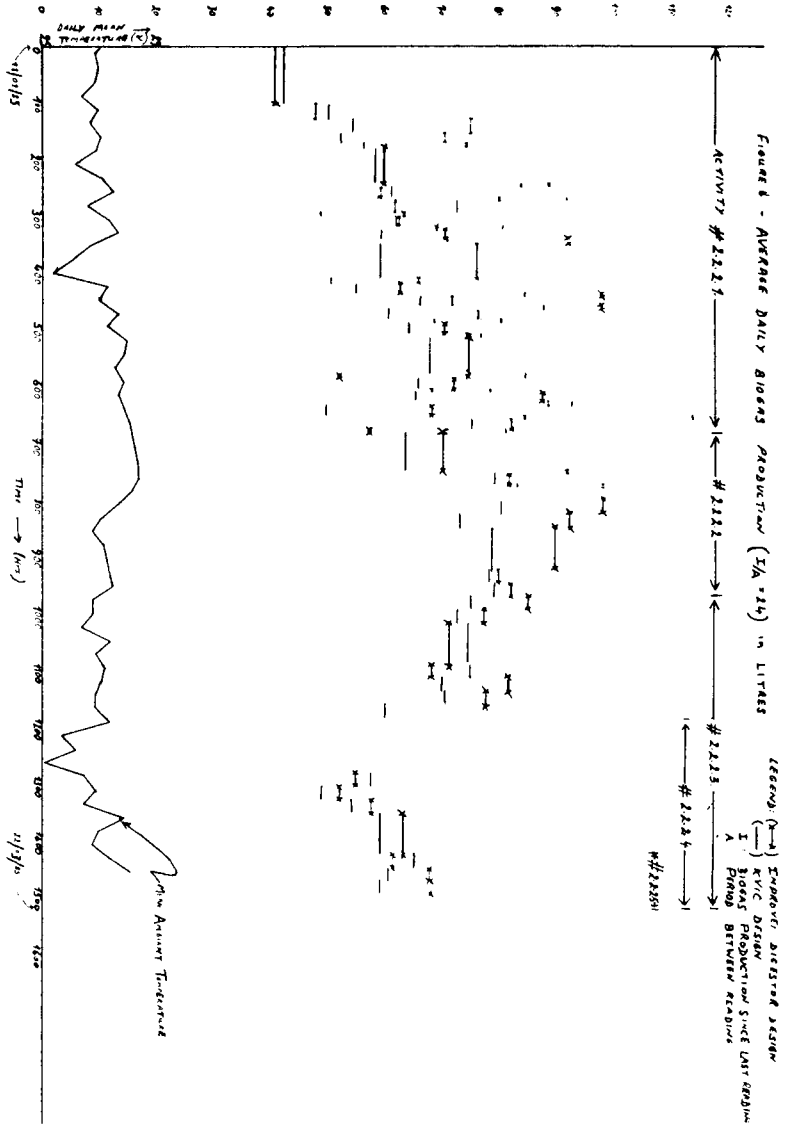


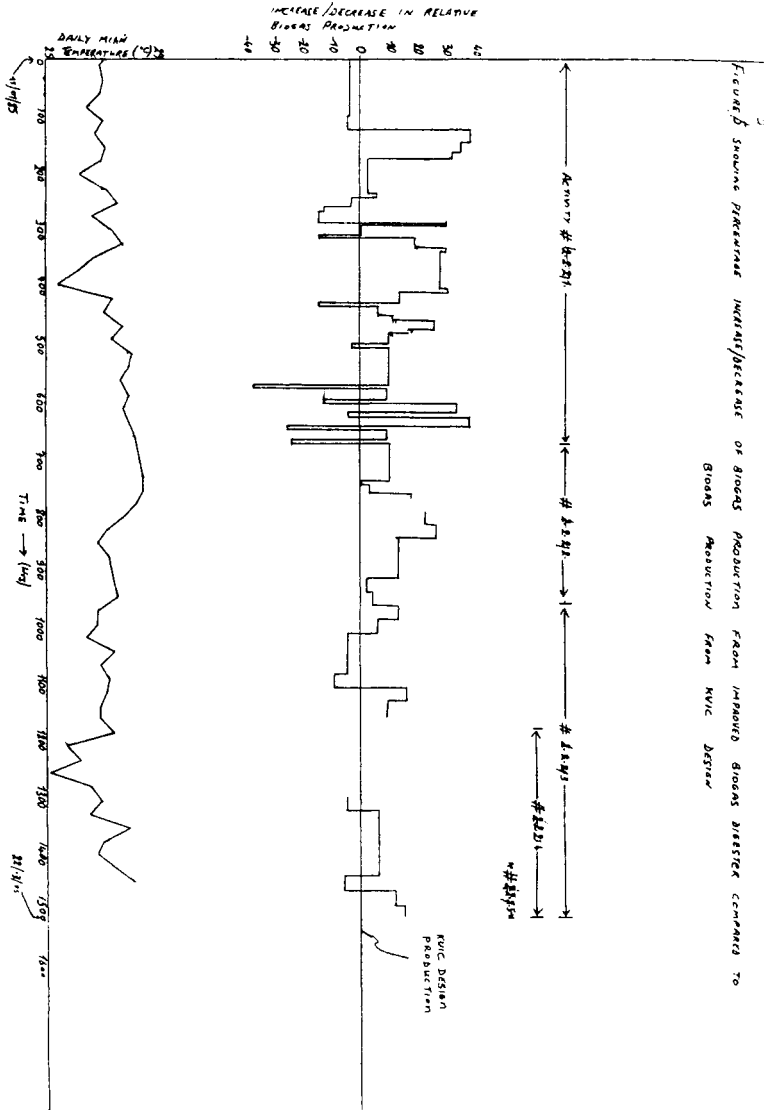
FIGURE 2: Improved biogas digester



**FIGURE 3: Average daily biogas production (1/A x 24) in litres**



**FIGURE 4: Percentage increase/decrease of biogas production from improved biogas digester compared to biogas production from KVIC design**



## **BIOGAS SYSTEM DEVELOPMENT IN MAURITIUS**

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### **ABSTRACT**

Experimental work on the anaerobic digestion of cow dung and sugar cane fibrous products (namely, cane tops and leaves, bagasse and filter mud) is reported. Cow dung proved a suitable raw material when anaerobically digested both under batch and semi continuous conditions in laboratory scale experiments. Results of the performance of a 2 m<sup>3</sup> overground metallic digester with floating gas holder (SAT I model) operating in a semi continuous mode and using cow dung are given. Economic analyses of this model operating at retention times (R<sub>T</sub>) of 10, 25 and 45 days and of an Indian KVIC model at R<sub>T</sub> of 45 days indicate that the SAT I model at short R<sub>T</sub> (of 10 days or less) is most attractive for cooking purposes in Mauritius.

### **INTRODUCTION**

The potential of biogas demonstrated elsewhere, has aroused much interest in Mauritius and research has focused on the potential for generating biogas from readily available materials. Such materials include animal wastes in the form of cow, poultry and pig manure and sugar cane agricultural and industrial wastes. Availability of these wastes and potential biogas yields have been estimated (Deepchand 1984). The cattle population in Mauritius includes 8000 units in large flocks (> 100 units) and 17000 units in small flocks (< 5). The excreta generated from animal husbandry has been estimated at 125000 Dm/yr (1980). This would produce an estimated 23 x 10<sup>6</sup> m<sup>3</sup>/yr biogas with an energy potential of 529 x 10<sup>9</sup> KJ/yr.

The clientele for biogas has been identified to be that currently using kerosene for cooking purposes (Baguant *et al* 1984). This clientele is found especially in the rural areas where potential raw materials are available.

This paper summarises research work carried out at the University of Mauritius with the financial support of ODA/CSC under the African Energy Programme. It includes experiments conducted to determine the yield and characteristics of biogas obtained through the anaerobic digestion of cow dung and sugar cane fibrous products. Subsequently based on the laboratory-scale experimental results, a system is proposed for a family biogas digester and the economic benefits of switching over to biogas as an energy carrier in the local context is analysed.

### **EXPERIMENTAL WORK**

#### **Batch digestion of cow dung**

As a first stage in this study, the anaerobic digestion characteristics of cow dung (CD) was studied in a 3-4 litre capacity digester. When required, starter culture was obtained from a batch digester at peak production and was mixed with CD:water slurry indicated on a total solid (TS) basis. Occasionally, foaming, scum formation and clogging of delivery tubes were encountered. Nevertheless, all experiments were performed in replicates.

To determine the effect of particle size, cowdung was sieved into three fractions: coarse (> 3.327 mm), medium (> 1.663 mm) and fine (< 1.663 mm) using a Tyler sieve shaker and all fractions brought to 10% TS prior to digestion. All digesters were stirred for 10 mins daily in the morning. Gas production was monitored daily and methane content at regular intervals by combustion in an Orsat apparatus.

In another experiment, a conventional drum type (100 l) digester with an inverted gas holder was used to monitor gas yield on a larger scale. Stirring was provided by daily rotation of the paddle fitted gas holder for about 10 mins.

## **Results**

The 100 l digester operating on cow dung mixed with an equal volume of water (C-D 1:1 TS) for 120 days gave the following results. There was an initial latency phase (35-40 days) during which daily gas production rates averaged 0.5 l/kg TS. Thereafter, for about 2 months, average production was 2.5 l/kg TS and total gas extracted after 120 days of digestion was about 200 l/kg TS. This is comparable to those reported elsewhere for digestion under similar conditions (NRC 1977). Methane (CH<sub>4</sub>) content of the gas produced ranged from 45 to 60% and mean calorific value 4-5 k cal/l after the latency phase.

The addition of a small amount of starter culture to the cow dung/water slurry considerably reduced the latency phase (Table 1). In the presence of 2.5% starter culture, latency period was reduced to about 6 days and cumulative gas extraction increased 4-fold by day 40 of digestion. No significant improvement was observed on increasing the percentage of starter culture to 10% TS. Consequently a 2.5% level of starter culture was routinely used in other experiments. Further addition of booster starter culture (between 2.5 and 10.0% TS) once digestion was established did not improve gas yield.

The optimum dilution for anaerobic digestion of cow dung under mesophilic conditions is 7.5 to 10% TS, which corresponds generally to a 1:1 cowdung to water ratio (Table 1). Sieving of raw material prior to digestion indicated that the finer portion of the cow dung is more easily digestible, although the differences as illustrated in Table 1 are relatively small.

The optimum temperature for anaerobic digestion of cow dung is about 35°C with a cumulative gas yield, after 20 days of digestion, of 104 l/kg TS or 4 times the yield at room temperature of 21°C (Table 1). Between 35 and 45°C there is marked decrease in gas extraction but under thermophilic temperature of 55°C after a slightly longer latency period (14 days) daily gas production rates were more than twice the corresponding values of digestion at 35°C. Under conditions reported here, optimum batch digestion at 35°C. Under conditions reported here, optimum batch digestion of cow dung at 35°C and in the presence of starter culture, would yield about 6 l biogas/kg TS/d after a latency period of one week.

Table 2 gives results of chemical analyses of digester input and output after various periods of digestion. The general fertiliser value of the slurry compared to the fresh cow dung is not diminished and, if anything, improved during digestion. Volatile solids and TS are reduced by about 25% during the 65 days of digestion and gas production (m<sup>3</sup> per TS or kg VS digested) is of the order of 0.6. This represents a thermodynamic conversion efficiency of 80% for the transformation of TS to CH<sub>4</sub>.

## Semi-continuous digestion of cow dung

### Laboratory studies

A 101 digester fitted with inlet and outlet delivery tubes and filled to an effective volume of 7 l with a 1:1 cow dung/water slurry and 2.5% starter culture was used for laboratory scale experiments. The digesters were kept at ambient temperature (19-21°C) and agitated once daily. Gas production was monitored over 21 days. After this, the digesters were loaded with the cow dung/water slurry at rates varying from 87g to 1400g (based on the mean retention time ( $R_T$ ) of 6.5, 12.6, 25.1, 37.8, 47.8, 61.4 and 96.2 days) in a semi-continuous mode of operation with daily (except Sundays) loading and removal of slurry. Total solids and volatile solids (VS) in effluent and influent were determined daily. Gas production was followed over a four week period and mean production (1/kg TS added, dig. vol.,  $D_V/d$ ) calculated for the last three weeks.

The cumulative gas yield for the last three week period varied from 33.7 l (96.2 d  $R_T$ ) to 72.5 l. (6.5 d  $R_T$ ) and gas production (1/kg TS added) varied linearly (70-220 l/kg TS) with  $R_T$  (that is,  $y = 1.85 R_T + 33$ ) varying from about 15-100 days (Figure 1). At shorter  $R_T$  or higher loading rate, the slope in the gas yield indicates a minimum  $R_T$  of four days for the successful operation of a semi-continuous digester. On the other hand, a gas yield in terms of  $D_V/d$  against  $R_T$  is a hyperbolic curve on the period 15-100 days  $R_T$  but slopes off at shorter  $R_T$ . Maximum yield under these conditions are observed at  $R_T$  of about 6 days (or 0.45  $D_V/d$ ). Extrapolation of the hyperbolic curve for  $R_T$  indicates the maximum extractable biogas under corresponding batch conditions to be about 0.21  $D_V/d$ . This is in agreement with the results obtained on batch digestion.

### Field Studies

To verify these results a digester was constructed to monitor biogas yield and characteristics under field conditions. The design consists essentially of a 2m<sup>3</sup> above ground metallic (stirrer fitted) digester with a floating gas holder. It was loaded with a mixture (assuming  $R_T = 25$  days) and operated at ambient temperature (mean of 22°C from January to April, 1984 with peaks of 25°C). The mixture was stirred twice daily for 10 mins.

Methane and CO<sub>2</sub> contents were determined at regular intervals. Tests on the possible utilisation of this gas (a) in a conventional household gas stove modified to operate on biogas and (b) to run a 4 KW, 4 stroke single cylinder diesel engine modified to accept biogas as a partial substitute to diesel, were also carried out.

The results in Figure 2 show that although mean ambient temperature varied between 21 and 25°C, the internal digester temperature was 34°C with occasional afternoon peaks of 40°C. Such temperature fluctuations are expected for that volume of water in a black metallic container during that period. No significant difference in pH was observed between the input and output slurry and it remained at around 6.9. The daily gas production rate was 0.5 dig vol/d and is twice that obtained under laboratory conditions (at 21°C) shown in Figure 1.

Methane and CO<sup>2</sup> contents were 45 and 55% respectively, and the calorific value ranged between 4 and 5 k cal/l which is to be expected of a gas with the above composition.

The efficiency of the modified stove based on the heat output (temperature rise for a given weight of water) and input (calorific value and volume of biogas used) ranged between 60 and 70%. This is higher than the efficiency of traditional kerosene cookers (40-50%). Diesel consumption in the single cylinder engine has been reduced by half at idling speed of 1500 rpm. Experiments are underway to reduce diesel consumption of the engine and operate at load conditions.

### **Anaerobic digestion of sugar cane fibrous products**

In the first set of experiments, an attempt was made to digest fresh samples of cane tops and leaves (CTL), fibrous residues (FR) and bagasse (B) and these fibrous products mixed with 50% cow dung (TS basis). Fresh cow dung served as a control. All the mixtures were diluted to 8% TS and allowed to digest (after inoculation with a 2.5% starter culture) in 4.5 l digesters at room temperature (20-22°).

Fresh sugar cane fibrous products proved to be poor substrates for anaerobic digestion. Over a 130 day period, the cumulative gas yield, which ranged from 8 to 13 l/kg TS for the 100% treatment, was negligible compared to the control (140 l/kg TS).

In the subsequent experiment, CTL were prepared in a Jeffco cutter grinder and allowed to compost for 20 days, then mixed with different proportions of cow dung and digested as described above. Figure 3 shows the cumulative gas production patterns.

All the curves assumed a general exponential shape for the first 40 days with the average biogas yields of 1.5, 1.6, 1.7, 0.9 and 0.1/kg TS/d for treatments I-IV respectively. This was followed by a lag phase which was of progressively longer duration with increasing proportions of CTL in the mixture.

Cane tops and leaves even when composted, are not easily biodegraded although they may have contributed to a limited extent in the total biogas yield in the various mixtures with cow dung.

Finally, CTL was mixed with different levels of cow dung and filter mud (FM). The various mixtures were allowed to digest at room temperature and yield and composition of the biogas and the pH were monitored at intervals over 150 days.

Figure 4 shows the cumulative biogas yield from the mixtures. In the initial phase of digestion until day 50, the gas yield from treatment 1 (cow dung alone) was higher than any of the other mixtures. At day 150, the cumulative gas yield was 215 l/kg TS for treatments 4 and 2, 195 for 3 and 5, 175 for 6 and 1 and 146 for 7. Addition of CTL and FM to cow dung appears to bring about an increase in gas yield only in the later stages of digestion.

The pH dropped initially to 6.2 in all mixtures except cow dung alone (which remained between 7.1 and 6.8 throughout) and mixture 8 (which was below 5.8 until day 140). Significant gas liberation took place concurrently with rise in pH in all the mixtures.

No significant difference in the ratio  $\text{CO}^2/\text{CH}_4$  was observed in the various mixtures over that period.

From the above experiments, it may be concluded that fibrous products are in general poor substrates for anaerobic digestion and have to undergo other forms of pretreatment prior to digestion. They are thus not considered in the next section dealing with the economic aspects of biogas production from cow dung and utilisation.

### ECONOMIC ASPECTS

The economic aspects of using a cow dung based biogas system for daily cooking (effective) energy requirements were examined. The total annual charges (TAC) resulting from setting up and operating the family biogas plant with the annual substitution value of the biogas were compared with the present costs to the consumer using various traditional cooking fuels. The SAT I 2m<sup>3</sup> digester used in the field trials described earlier and an Indian KVIC underground digester commissioned by the Rural Development Unit (Ramdin 1984) were used in the evaluation. Both are meant to provide 1.5 m<sup>3</sup> of gas daily which would meet the daily cooking energy requirement of a typical Mauritian family.

The expected lift time (n) of the digesters is 10 years, the interest rate (i) on borrowed capital is 12.5%, operating and maintenance cost (a) is 4% and the fixed annual charges (FAC) is based on the levelised payment arrangement (Grant and Ireson 1984). The total annual charges (TAC) are given by the formula

$$\text{TAC} = \text{FCI} \left[ \frac{i(i+1)^n}{(i+1)^n - 1} + \frac{a}{100} \right]$$

where FCI is the fixed capital investment. Total annual charges for the two models are shown in Table 3. It is assumed that the cost of cow dung, labour for its handling and storage and the spent slurry is zero. The TAC are included for the SAT I model operating at R<sub>T</sub> = 10, 25 and 45 days which would require 64, 53, and 43 kg of cow dung daily. The FCI of these models is based on the power relationship (Peters and Timmerhaus 1968):

$$\text{FCI (expected)} = \left( \frac{V_e}{1750} \right)^{0.8} \times \text{FCI (actual)}$$

where V<sub>e</sub> = effective volume of required digester, and FCI actual = Rs 6000 for a digester 1750 l effective volume.

The amount of money spent by the typical Mauritian family for cooking purposes is, Rs 420, 1585, 1880, 2710 and 3080 for firewood, kerosene, wood charcoal, electricity and LPG respectively (Baguant et al 1984).

Using the KVIC model, the family using firewood, kerosene or wood charcoal would suffer an annual net loss of Rs 1825, 771 or 506 respectively. The system seems only marginally attractive for electricity or LPG users with net differences of Rs 244, or 579 (or 20% of the domestic cooking energy bill) because such users belong to a class who can afford such a cooking energy bill.

With the SAT I model operated at high  $R_T$  (of 45 days), the same comments as above apply. However, with reduced  $R_T$ , the SAT I model becomes more and more attractive to users of high cost fuels (electricity and LPG). For example at  $R_T = 25$  days, the net annual benefits increases to 25% of the domestic cooking energy budget for these two categories of users. At  $R_T = 10$  days (or even 4-6 days) the system becomes attractive to all users (except those using firewood) with net benefits ranging from 25% for kerosene users to 57% for LPG users.

The foreign exchange involved in the construction and installation of the SAT I model operated at short  $R_T$  would also be comparable to that of the KVIC model (Rs 2800 and 3500 respectively).

With some further refinements in the operation of the SAT I model, it is felt that, with a biogas plant of  $1.3 \text{ m}^3$  effective volume costing around Rs 5000, it would be possible to produce  $1.5 \text{ m}^3$  of gas daily. Successful operation of such a unit (which is under way) would thus enhance the case for popularising biogas technology in Mauritius.

### **CONCLUSION**

It has been demonstrated in this study that it is technically feasible to produce biogas from cow dung. It would be economically attractive to all categories of energy users for cooking purposes when it is operated at short retention times (10 days or less) in the SAT I model which would involve capital investment of around Rs 5000 and total annual changes of Rs 1027. The attractiveness of the family biogas systems in the local context would increase if it were possible to produce  $1.5 \text{ m}^3$  of gas from a digester of  $1.3 \text{ m}^3$  effective volume which would require a daily supply of 65 kg of cow dung (slightly higher than the 50 kg required in the KVIC model).

Such a system, if successfully popularised, would bring about significant savings in foreign exchange required for importing kerosene and would, at the same time, diminish the deforestation pressures. However, hasty marketing of technically inappropriate or economically unattractive family biogas systems carries with it serious risks of disenchantment and backlash against biogas technology as a whole. For example as shown in this study, biogas produced from the KVIC model is not competitive with either kerosene or wood charcoal unless massive levels of government assistance is envisaged. Accumulation of material at the bottom of the pit (underground) which would block digester operation and necessitate particularly difficult clean up procedures, is a technical problem that has yet to be resolved.

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**TABLE 1: Batch digestion of cow dung**

Experiment	Temp °C	Starter culture % by Wt	TS % by Wt	Cumulative gas yield (1/kg TS)	
				20 days	40 days
	28	0	10.0	10.1	36.7
Effect of starter culture	28	2.5	10.0	76.0	133.0
	28	5.0	10.0	80.6	138.0
	28	7.5	10.0	83.0	140.0
	28	10.0	10.0	83.1	137.0
Effect of dilution	23	2.5	2.5	23.0	63.0
	23	2.5	5.0	25.0	65.0
	23	2.5	7.5	26.0	64.0
	23	2.5	10.0	26.0	70.0
Effect of particle size	F 23	2.5	10.0	30.4	87.4
	M 23	2.5	10.0	28.4	73.0
	C 23	2.5	10.0	25.0	65.0
Effect of temperature	21	2.5	10.0	26.0	
	30	2.5	10.0	68.0	
	35	2.5	10.0	104.0	
	40	2.5	10.0	64.0	
	45	2.5	10.0	9.6	
	55	2.5	10.0	76.6	

**TABLE 2: Fertiliser value of slurry at various stages of digestion**

Sample (Days)	Total solids		Volatile		Cumulative gas		Nitrogen		Phosphorous		Potassium	
	%	% TS	% TS	L	Total % TS	Available % TS	Total % TS	Available % TS	Total % TS	Available % TS	Total % TS	Available % TS
0	8.92	88.19	88.19	0	1.25	0.37	0.50	0.50	0.55	0.49	0.55	0.49
6	8.63	87.95	87.95	2.30	1.25	0.47	0.58	0.55	0.55	0.50	0.55	0.50
10	8.59	87.55	87.55	5.15	1.08	0.47	0.58	0.55	0.55	0.54	0.55	0.54
21	8.21	87.03	87.03	20.70	1.23	0.47	0.58	0.57	0.60	0.56	0.60	0.56
41	7.47	85.20	85.20	44.26	1.50	0.65	0.73	0.64	0.61	0.58	0.61	0.58
65	6.73	84.64	84.64	52.50	1.50	0.65	0.88	0.65	0.67	0.63	0.67	0.63

**TABLE 3: Total annual charges and net annual benefits in using biogas for the SAT I and KVIC digester models**

	SAT I model			KVIC underground model
	Retention time (days)			
	10	25	45	40
<u>Total annual charges</u>				
V <sub>e</sub> (l)	1280	2645	3855	3800
Daily cow dung required (kg fresh)	64	53	43	50
FCI (Rs)	4670	8350	11,300	10,000
FAC (Rs)	840	1503	2034	1806
Op & M (Rs)	187	334	452	400
TAC (Rs)	1027	1837	2486	2206
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<u>Net annual benefits (Rs)</u>				
Firewood*	-647	-1457	-1056	-1826
Kerosene*	408	-402	-1051	-771
Wood charcoal*	673	-137	-786	-506
Electricity*	1423	613	-36	244
LPG*	1758	948	299	579

\* If above fuel used throughout the year for cooking, the annual expenses are: Rs 420, 1585, 1880, 2710 and 3080 respectively.

FIGURE 1:  $R_T$  V/S gas production for semi continuous digester

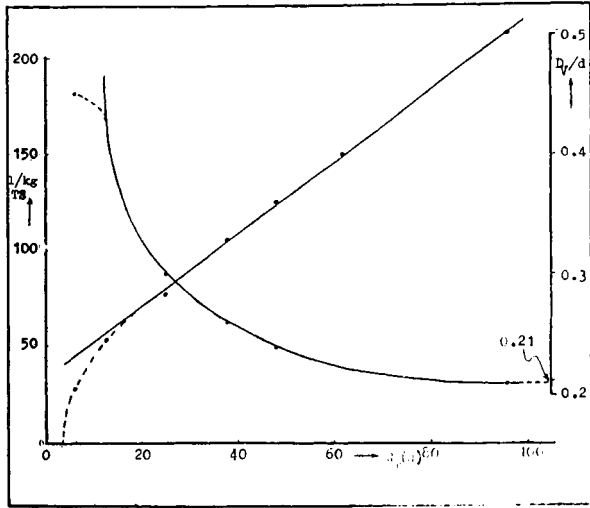
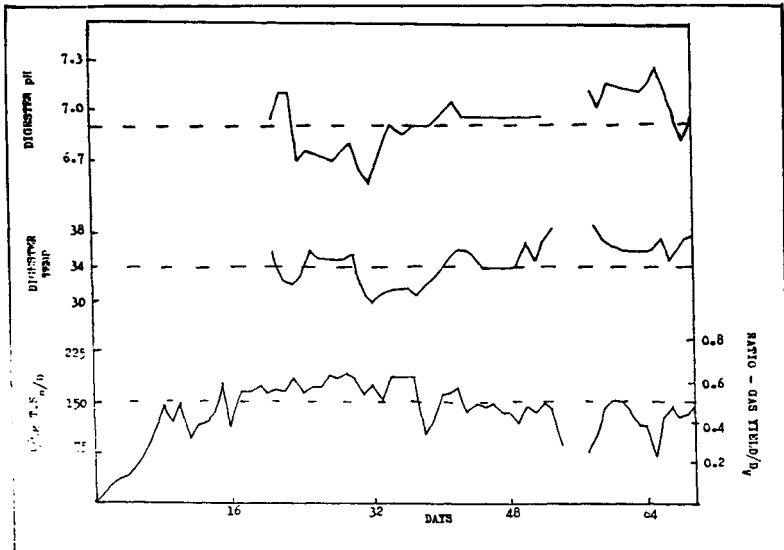
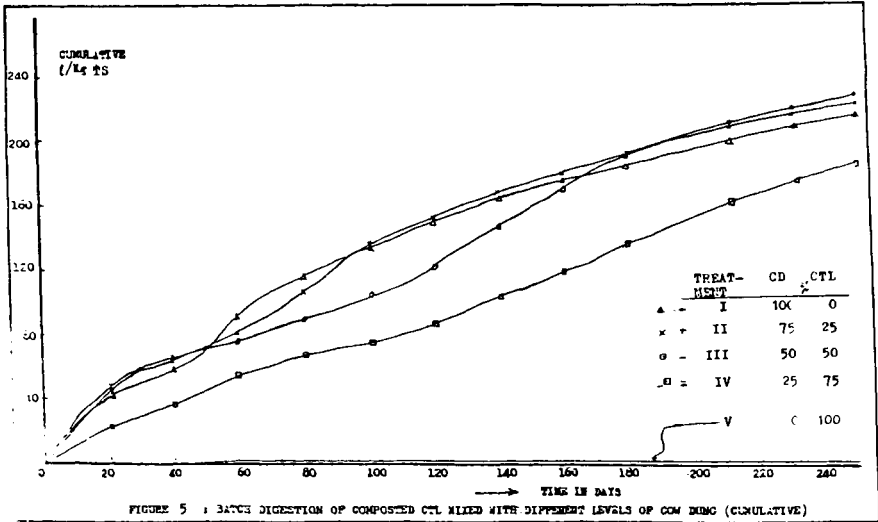


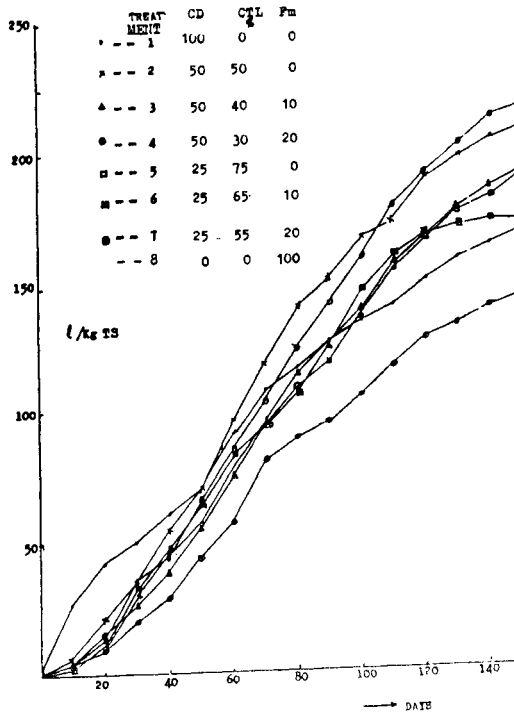
FIGURE 2: Performance of family size semi-continuous digester (SAT-I model)



**FIGURE 3: Batch digestion of composted CTL mixed with different levels of cow dung (cumulative)**



**FIGURE 4: Cumulative biogas yield from different treatments**



**THE DIFFUSION OF FAMILY-SIZE UNIT BIOGAS PLANTS IN  
SUITABLE AREAS IN TANZANIA - THE DEVELOPMENT OF AN EXTENSION STRATEGY**

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**ABSTRACT**

Past efforts to extend biogas technology have not been very successful. The technology is complicated, selection of appropriate sites needs to be carefully planned by experienced specialists, and biogas know-how must be transferred to the villages concerned. The Biogas Extension Strategy described here aims to instruct village artisans in the construction of cheap and appropriate biogas plants.

**BIOGAS TECHNOLOGY IN TANZANIA**

Since the beginning of 1984 CAMARTEC has been stressing the extension of biogas plants (BGP) in Tanzania. Activities date back to 1974. Many demonstration plants have been set up, technicians trained and much money spent. Unfortunately, a great number of plants are not working.

**MISTAKES IDENTIFIED IN FORMER BIOGAS PROGRAMMES**

A wide range of mistakes have been identified, which can be divided into three main fields:

1. Selection of locations. Many plants have been set up at places which do not fulfil the criteria for successful operation. Often it was difficult to transport the required amount of dung or it was easier and more logical to use other sources of energy.
2. Technical mistakes. Many plants are not working due to inappropriate design or poor workmanship, especially in the parts that need to be gastight such as the gasholder and the piping.
3. Training of involved persons and follow up supervision. Very often the basic technical knowledge is not clear to the users. Therefore small mistakes in the operation of the plant, the lamp and the burner are very common, the accumulation of which can easily lead to a final failure.

**PRECONDITIONS FOR SUCCESSFUL BIOGAS EXTENSION PROGRAMME**

In developing a new biogas extension programme, criteria were laid down to overcome past problems.

### **Criteria of suitability for locating a biogas plant**

Among the most important prerequisites for a successful programme for biogas diffusion are the following:

- i. High population density which creates pressure on available energy sources.
- ii. Sufficient vegetation density to allow cattle rearing in stables without recourse to grazing.
- iii. Concentrated animal husbandry - for instance three cattle confined to a stable for 24 hours a day as a minimum.
- iv. High intensity of land usage to create a need for fertilisers and systematic disposal of wastes.
- v. A sufficient degree of monetarisation of the farming economy so that there is an economic incentive for digester construction and the use of gas and fertiliser.
- vi. A technical capability for brick or concrete construction and a level of technical awareness sufficient to operate and maintain a digester.

### **Digester design**

Digesters distributed in Tanzania are either copies of the Indian technology where the gas is stored in a floating drum or a modified Indian Plant. The latter while much cheaper is extremely unreliable, because scrap metal used to make the gasholder corrodes quickly. The high costs or unreliability are the main reasons why individuals have not copied demonstration plants.

This first extension trial did not include Chinese fixed dome technology. The advantage of the fixed dome technology is that almost no steelwork is involved. This reduces the costs of materials and makes the setting up and the supervision easier. However, the construction of a fixed dome is difficult and requires trained masons. Thus introduction of such a biogas plant must include training of local artisans in specific building techniques to ensure that the upper part of the fixed dome is crack resistant, gastight and can stand changing pressures. The workmanship must follow precise specifications to function correctly.

Provided appropriate training and supervision were made available, the Chinese fixed dome biogas plant was felt the most suitable to rural Tanzania and this technology forms the basis of the biogas extension project described below.

### **Sensitive engineering**

The practical development of biogas technology requires not only technological know how but also experience of the traditions of the target group, and especially of users reaction to this technology. Appropriate technology evolves through learning from mistakes and drawing conclusions from failures.

Extendable technology cannot be achieved by copying systems that proved successful in other countries or cultures. Instead of instructing farmers how to make a biogas plant by themselves, potential users must have the opportunity to

buy technology appropriate to their situation and culture. Therefore a supply of good quality biogas plants has to be developed in cooperation with the target users. Experienced experts must be available to advise and supervise to ensure the plant is set up properly. And these skills may be transferred to local artisans who will then promote and extend the dissemination of the technology within their communities.

### **STANDARDISED FAMILY UNITS**

For a family size biogas plant to be accepted the engineering input must be reduced. Therefore CAMARTEC developed three standardised fixed dome BGP of different capacities and provides training of technicians and local artisans in their construction. Figure 1 is an example of the design specification for a CAMARTEC fixed dome biogas plant. Tables 1-3 show the requirements and present costs for construction.

### **BIOGAS PLANT AND STABLE WITH CONCRETE FLOOR FORMING A "UNIT"**

To reduce maintenance requirements and daily work input, the family-size BGP is directly connected to a stable with concrete floor. Twice a day the dung is mixed with the urine which has accumulated in a canal in the stable. It has to move down into the digester through a 4" pipe. To make it liquid enough it can be mixed with already digested sludge which is taken from the expansion chamber. Water can also be used, but it has the disadvantage that it has to be carried for a long distance in most cases.

In the case of an existing stable with a dung or soil floor, a concrete floor will have to be constructed even if it increases the costs by about 20%. The concrete floor will ensure a 100% urine and dung collection, an easy filling of the plant and helps to avoid stones and sand from entering the digester.

In general the increase in investment costs is justified, if it helps to reduce the daily work input and increases the reliability of the system.

### **METHOD OF DIFFUSION**

If a technically appropriate solution is found, a method of disseminating the technology is essential. In general there are two methods. The first one is to establish a team of artisans within an organisation that supplies individual customers. This increases the costs and automatically the customers will mainly be big farmers.

The second way is to train artisans who live in areas that comply with all the feasibility criteria. If the supplier lives in the neighbourhood, the demand from surrounding farmers will follow. Most customers will be small-scale farmers with an additional source of income.

The second approach seems to be the more complicated one and will therefore be described in more detail. The aim is to supply as many farmers as possible with BGPs and at the same time to transfer the know how to local artisan.

The programme is carried out in three main steps:

1. A survey is conducted to estimate the potential of farms suited to operate a BGP. A questionnaire is used to determine the energy situation, the

farming system, the availability of digestible material and water and the financial situation.

2. Where a demand for BGPs is identified the technology will be introduced to the village government and interested farmers. This will be done either by setting up a small transportable demonstration unit which supplies a small amount of gas or by organising a site visit to an operating BGP.
3. Selection of a suitable site where the first unit of the particular village is installed. The construction is done by two artisans from the village and supervised by CAMARTEC Biogas Extension Service who will be conducting on the job training. Experience has shown that demand follows initial construction.

Supervision can be reduced as successive plants are constructed. The village artisans are the main suppliers to satisfy the demand.

To ease and accelerate the process for the individual farmer of purchasing the requested building material, CAMARTEC is establishing a material supply store which also supplies lamps and burners. A step in the future will be also to produce these in the country.

The other task of CAMARTEC, within this strategy, is to advise on individual biogas problems, eg planning, construction, feeding, gas production, gas consumption, use of sludge and maintenance.

### **PRELIMINARY DIFFUSION AREA**

In the Arusha region, an area of 200 sq km was identified as satisfying the criteria for introducing biogas technology. There are roughly 7000 farms in this area and 20,000 heads of livestock of which at least 50% are kept in stables. Ten per cent of the farmers were definitely interested in biogas technology and could afford the technology.

### **COSTS AND BENEFITS**

The investment costs are comparatively high. However converting the amount of gas produced into commercial energies which represent the families newly achieved standard of living, a biogas plant would break even in 3-4 years, including running costs and interest repayments.

However, farmers and especially the farmers' wives have identified shorter-term criteria in support of installing a BGP:

- i. The increasing difficulty of getting firewood and kerosene.
- ii. Quick and reliable preparation of small things like tea as well as the normal cooking.
- iii. Light in the evening.

Farmers interested in obtaining BGPs have tended to be innovative and business oriented. The first four farmers started to convert surplus energy into marketable food products, eg brewing local beer, baking bread or pancakes, or roasting their own coffee in order to sell it.

Figure 2 estimates the preconditions to expect an excessive supply of gas and the capacity of BGP to satisfy the needs of farms of different sizes.

### **THE FERTILISER**

The sludge from BGPs is a very good fertiliser. While not always included among the benefits of the biogas technology and under utilised, its advantages include the following.

- i. With zero-grazing and confined to a stable with concrete floors, all wastes from the animals are collected.
- ii. The sludge from the digester contains the same amount of nitrogen as the original manure. Traditional ways of storing manure results in major losses of nitrogen.
- iii. There is no risk from contamination by chemicals and the fertiliser is easily assimilated by plants.
- iv. Slurry fertiliser does not smell or attract flies.

Nevertheless, only a minority of BGP owners utilise this fertiliser. It seems that the disadvantages are major as follows:

- i. Transportation of liquid slurry in wheelbarrows or in buckets is difficult.
- ii. There is run off and therefore loss of fertiliser.
- iii. The fertiliser is most effective when applied to roots, under wet and cloudy conditions, at the stage of intensive plant growth. These pre-conditions occur seasonally while sludge is produced continuously.

The Biogas Extension Programme has to incorporate these findings.

### **STEPS IN THE FUTURE**

The Biogas Extension Programme in the Arumeru District will be extended to other suitable areas. For success, the following aspects need further emphasising:

1. Involvement of private entrepreneurs in plants and construction of accessories. 2. Surveys to estimate the potential number of farms suitable for biogas plant operation.
3. Development of teaching aids and regular training for further training of artisans and technicians.
4. Establishment of a maintenance team.
5. Ensure expert advice on all fields involved in the technology with the help of appropriate booklets and well equipped advisers.
6. Continuous reassessment and improvement of standardised plants.
7. Development of prefabricated building material.
8. Development of methods and instruments for appropriate use of fertiliser.

**TABLE 1: List of requisites required for the three CAMARTEC fixed dome standard biogas plants (BGP) (all metric figures). For requirements which are different on each farm see Tables 2 and 3**

Item	Unit	Standard digesters					
		Small family BGP (8 m <sup>3</sup> )		Medium family BGP (12 m <sup>3</sup> )		Big family BGP (16 m <sup>3</sup> )	
		amount required	costs 1)	amount required	costs 1)	amount required	costs 1)
Bricks 8 x 11 x 22	pieces	750	2250	1150	3450	1400	4200
Cement	50 kg bags	10	2000	14	2800	17	3400
Lime	25 kg bags	4	600	6	900	7	1050
Sand Stones	kg	2500	1200 2)	4000	1600 2)	5000	2000 2)
Plastic pipe - 4"	6 m	1	500	1	500	1	500
Hole to be dug	cbm	20	400	26	520	33	660
Mason	Lump sum	1	1800	1	2500	1	3000
Helper	Lump sum	1	1400	1	1600	1	2000
Other Material 3)			400		500		600
<b>TOTAL</b>			<b>10,550 TSH</b>		<b>14,370 TSH</b>		<b>17,410 TSH</b>

1) All prices relate to 2/85

2) The price for sand can differ extremely

3) Other materials, eg kerosene and wax for gastight sealing, clay for lid sealing, reinforced gas outlet pipe, handles for lid.

**TABLE 2: Materials and other requirements including costs per constructing the stable floor**

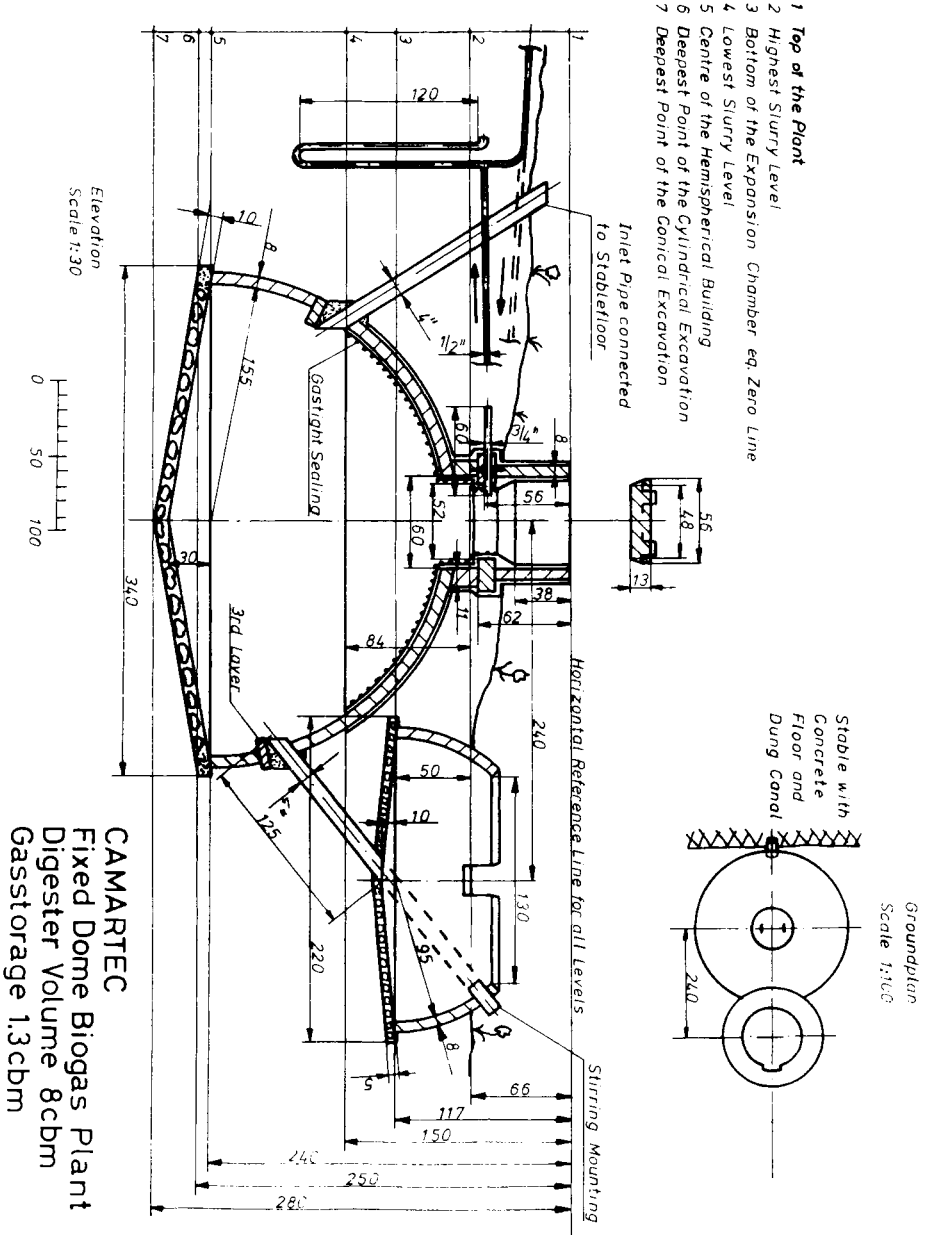
Item	Unit	Type of stable			
		Cow shed or sheep pen		Pig sty	
		amount/(10m <sup>2</sup> )	price (TSH)	amount/(10m <sup>2</sup> )	price (TSH)
Cement	bags	3	600	5	1000
Sand stones	kg	2000	1000	4000	2000
Mason			300		500
Helper			200		300
<b>TOTAL per 10 m<sup>2</sup></b>			<b>2100</b>		<b>3800</b>

**TABLE 3: Gas consumption accessories**

Item	Purchased through	price (TSH)
Burner	CAMARTEC	700
Lamp	CAMARTEC	500
Pipe 1/2"	1m* CAMARTEC	80
Pipe 3/4"	1m* CAMARTEC	110

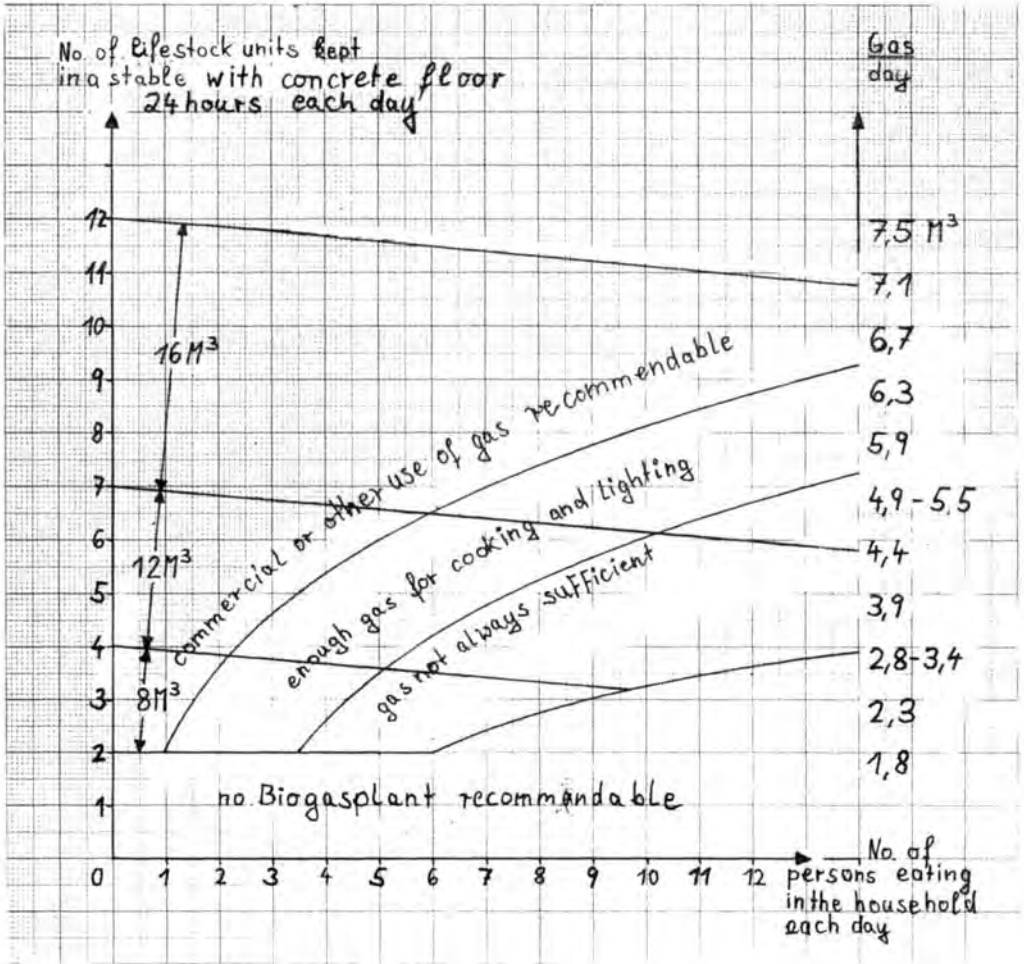
\* Average price, including fittings and one valve and the installation work.

**FIGURE 1: CAMARTEC fixed dome biogas plant digester: 8 cbm volume with 1.3 cbm gas storage**



**FIGURE 2: Means for first estimating the appropriate standard unit.**

All figures are related to the described unit and the cooking habits of the people in Arumeru District of Tanzania.



## **BIOGAS TECHNOLOGY FOR RURAL DEVELOPMENT IN ZIMBABWE**

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### **ABSTRACT**

This paper reports laboratory experiments of the anaerobic digestion of pigeon droppings and waste material from coffee processing and the application of these findings in field trials using three types of biogas digesters designed and built in Zimbabwe. It is concluded that biogas technology may be a feasible solution to the shortage of wood-fuel and fertiliser in the rural areas.

### **INTRODUCTION**

Although biogas generation is already a well known technology in countries such as India and China, many people in Zimbabwe are not familiar with this technology. A biogas project, described in this paper, was launched to develop and promote biogas technologies for use in the rural areas of Zimbabwe through investigations into user needs, feedstock for biogas digesters and utilisation of the biogas and slurry.

### **LABORATORY WORK**

Prior to initiating wide scale field trials, laboratory investigations were conducted to determine the amenability to anaerobic digestion, quality of gas produced ( $\text{CH}_4$  content) and optimum pH, temperature and retention time for various potential substrates. The necessary modification of existing cooking and lighting appliances to operate on biogas has also been investigated.

### **Evaluation of the performance of biogas substrates**

A crop residue, wastes from coffee production, and an animal waste product, pigeon droppings, were tested in a laboratory scale biogas digester. The digester was maintained at a constant temperature throughout. Total solids (TS), volatile solids (VS), fixed solids (FS) and volume of gas produced and pH of the slurry were measured.

### **Results**

The biogas obtained from coffee wastes was almost odourless, indicating very little hydrogen sulphide. Gas from pigeon waste was fairly odorous.

Mixing of digester contents by occasional hand swirling, proved inadequate in the case of coffee waste which tended to froth and form a floating scum which at times rose and blocked the gas outlet.

An analysis of the substrate used is presented in Table 1 and the amount of gas produced over a 16 week period is presented in Table 2.

### Discussion

Crop and animal waste produce biogas of slightly different composition. Gas chromatography would be necessary to determine the actual composition of the gas. A number of problems were encountered including the following:

- a. There was difficulty in obtaining representative samples for total solids and volatile solids because of the heterogeneous particle size of the coffee waste. Because only small samples were collected, the presence of a large solid lump would raise the TS value obtained with that sample.

Grit present in pigeon waste caused similar problems and had a marked effect on the weight of the ash left in the crucible when the VS had been driven off. In this case, it is advisable to collect the samples at a fixed time after swirling the digester.

- b. The coffee waste particles trapped gas bubbles and were buoyed to the top of the slurry, leaving most of the liquid below. The particles were then slowly lifted by the gas from the liquid layer until they blocked the gas outlet. This tendency to float was countered by frequent stirring to release trapped gas bubbles.
- c. There was a gradual build-up of grit at the bottom of the digester due to its presence in the pigeon waste. It was therefore found necessary to empty the digester and remove the grit occasionally.

### Research on appliances

Household appliances in Zimbabwe are relatively crude and inefficient. Local manufacturers have concentrated on cookers for both high and low pressure bottled gas. Some high pressure gas lamps have also been manufactured. Work has been carried out to modify some of these appliances to use biogas.

#### Cookers

Most biogas cookers currently used in rural Zimbabwe do not include the pre-mixing of biogas with air. We investigated the performance of these cookers with and without pre-mixing of biogas. The advantages of pre-mixing are presented in Table 3.

#### Gas Lamps

The commercially available cadac gas lamp has a small jet and this does not allow gas to flow freely. The jet was enlarged to a diameter of just over 1mm to provide the required richer gas:air mixture. Gas delivered at a constant pressure of 10-20cm water column above atmospheric provided a steady flame. Undried gas gave only half the rated illumination of the lamp. Work is now being carried out to fabricate a low cost Indian-type biogas lamp.

### FIELD TRIALS

Biogas technology was introduced to the rural people in the form of various demonstration digesters described in the following sections.

### Oil drum digester

A 200 litre oil drum was filled with cow dung slurry and completely sealed leaving an outlet for the gas. The gas was stored in an inner tube obtained from a local bus company. A small tin stove was connected to the inner tube. This digester was used as a demonstration model at agricultural shows.

### Domboshava biogas plant

This digester was based on an Indian design of fixed brick-lined digester. The pit was shallower because of the possibility of striking a high water table which would have cooled the sludge to some degree. The materials used to build the plant were as follows:

2500 fire burnt bricks	25 x 50kg packets of cement
230 metres (10 gauge) wire	35 metres (12mm) reinforcing rods
5 litres epoxy pitch black paint	6 metres (150mm int dia) asbestos P
3.8 metres (75mm) galvanised pipe	1.3 metres (100mm) galvanised pipe
1 gate valve	1 base plate
4 (100mm) bolts and nuts	1 gasometer tank
5 kg bittumen sealant	Hose pipe and clamps as required
5 litres aidpol	according to distance.

The digester was built within a few days and operated on sludge from one of Harare's sewage works. Enough gas was being produced within a week to provide for cooking in a nearby building and to run a refrigerator once the jet had been enlarged slightly. A caravan-type gas lamp did not work as satisfactorily as the cooker.

The gas produced contained: 69% methane; 21% carbon dioxide; and 10% nitrogen and other gases.

Gas production was measured during the day, during the night and between Friday evening and Monday morning (the weekend). Overall production and consumption in cubic metres are as follows:

	<u>Produced</u>	<u>Consumed</u>
Day	10,572	17,749
Night	5892	0
Weekend	4155	0

The average daily gas production was estimated to be 0.570 m<sup>3</sup> during winter days and 1.2m<sup>3</sup> during summer days. About 7.5 kg of cow dung was fed into the digester every day except over the weekends. This gave gas production of 0.076m<sup>3</sup> per kg in hot months.

### **Chishawasha biogas plant**

This plant based on a Chinese design of 3m<sup>3</sup> capacity was built for a family in the rural area near Harare. Materials used for the digester were as follows:

13 x 50kg cement	1 brass gate valve
	700 bricks
7 kg impermo (waterproofing compound)	1 x 50kg building lime
5 kg sealing putty	6.65 m galvanised pipe (20mm)

Local people were trained on site to build the digester. Difficulty was encountered in building the dome, which was shaped by using a pole with a flat board (approx 150 mm x 75 mm) perpendicular to its end. The total length of the pole from the bottom to the surface of the board was R mm which was the radius of curvature of a sphere. The bottom of this pole rested on a support at the centre of curvature of the dome and each brick was positioned by using the board on this pole. The walls were plastered and painted with bitumen paint.

The digester operated on cow dung sludge. The gas was piped to the kitchen. Inner tubes of bus tyres were used for storing gas. This arrangement helped to maintain a steady gas flow to the kitchen. The gas was used mainly for cooking.

### **Adelaide acres biogas plant**

At Adelaide Acres, a centre for training cooperative personnel, a demonstration digester using night soil was constructed.

An ordinary septic tank was converted into a digester by casting a concrete slab on top. The manhole was modified so that a lid with a gas pipe could be fitted. The inside was plastered with waterproofing plaster and painted with bitumen paint. Water from the showers and hand basins was diverted away from the digester so as not to further dilute the slurry.

The gas from this digester was passed through another small Indian type digester and collected in the gasholder. The gas was piped to the kitchen where it was used for cooking. Gas production could not be measured but a meter was fitted to measure the gas consumption.

Coffee waste and left over maize meal were used in this digester because cow dung was not easily available.

### **Kushinga Phikelela Biogas Plant**

Kushinga Phikelela is an Agricultural Institute situated about 100 km east of Harare. The place was chosen for demonstrating the generation of electricity using biogas.

An 80 m<sup>3</sup> steel digester was erected. Biogas was stored in a floating gas holder and a butyl-rubber balloon. The spent slurry was stored in 60 m<sup>3</sup> lagoon. The important plant electrical loads are as follows:

- 1 10 kw feeding pump

- 1 3 kw mixing pump
- 1 0.8 kw fan coil
- 1 3 kw stirring pump
- 2 0.7 kw hot water circulating pump

The digester was fed mainly with cow dung although occasionally mixed with left over maize porridge from the kitchen. Gas production averaged about 2.5 cubic metres per hour. The gas engine consumed 15 cubic metres of gas per hour. The gas is used mainly to generate electricity for the milking place in the morning and evening.

Table 4 gives an indication of the cost of constructing an Indian type of biogas plant using local materials and labour. Costs for a Chinese type would be similar but does not require a gasholder and hence labour costs for welding it.

### CONCLUSION

The various field trials have illustrated various degrees of success. Problems encountered so far have been as follows:-

- poor construction of digesters due to lack of proper know-how
- difficulties in maintaining and managing the plants. This was particularly noticed at schools where nobody took charge of the plant. Individual households managed their plants efficiently.
- lack of proper communications between researchers and beneficiaries. This is due to lack of transport for researchers and development officers.

Biogas technology is becoming more popular in rural areas. A number of plants have been built so far (Table 5). Most of the plants can be regarded as technically successful. They provide gas for cooking and also a certain amount of lighting. The excellent crops of maize and vegetables grown in the vicinity of the plants bear testimony to the excellent quality of the fertiliser produced in the digesters.

TABLE 1: Characteristics of two biogas substrates

Component	Pigeon waste		Coffee waste	
	% of Feed	% of TS	% of Feed	% of TS
H <sub>2</sub> O	6.33	0.00	83.76	0.00
TS	93.67	100.00	16.24	100.00
VS	33.96	36.26	12.41	76.37
FS	59.71	63.74	3.84	23.63

TABLE 2: Biogas production over 16 weeks

Time (wks)	Coffee waste			Pigeon waste		
	Ave. gas yield m <sup>3</sup> kg <sup>-1</sup> VS day <sup>-1</sup>	VS %	TS%	Ave. gas yield m <sup>3</sup> kg <sup>-1</sup> VS day <sup>-1</sup>	VS %	TS %
1	0.14			0.42		
2	0.12	11.00	2.84	0.31	36.60	1.07
3	0.15	13.00	3.07	0.35	42.94	1.64
4	0.13	12.20	3.72	0.23	48.10	2.14
5	0.11	11.30	4.36	0.23	51.95	3.83
6	0.13	11.80	5.03	0.26	39.09	6.30
7	0.10	13.60	6.82	0.09	32.45	8.66
8	0.07	16.20	2.82	0.06	33.13	8.00
9	0.05	18.80	4.88	0.06	32.29	8.70
10	0.25	22.30	6.07	0.06	37.22	3.54
11	0.45	27.60	6.44	0.15	40.00	4.86
12	0.35	30.80	6.85	0.17	39.48	5.10
13	0.62	32.80	7.84	0.34	44.41	6.78
14	0.37	30.10	8.28	0.26	46.02	6.35
15	0.14	30.70	7.81	0.32	43.61	7.74
16	0.04		8.18	0.13	43.52	7.68

**TABLE 3: Advantages of premixing biogas with air**

With Premixing	Without Premixing
Complete combustion	Incomplete combustion
Air supply adjustable	Carbon monoxide formation
High efficiency heat to cooking vessel	Low thermal efficiency
Saves gas	Wasteful of gas
High temperature	Low temperature
Short clean flame	Long, wavy and sooty flame
Non conscious flame	Luminous flame

**TABLE 4: The following materials are required for a 10cm<sup>3</sup> Indian type plant which was found suitable for a family. For the Chinese type plant the gasholder and labour costs for welding are not required**

	Quantity	Approximate Cost
Cement	30 bags	150.00
Bricks (common)	3000	Not normally bought
Sand (river and pit)	-	"
Stone	-	"
Reinforcing wire mesh	Approx 10m	30.00
Paint (bitumen) + thinners	15 litres each	70.00
Impermo (waterproofing compound)	48 kg	65.00
Gasholder tank	1	310.00
Pipes and valves	3 valves 15" pipes	76.00
Inlet and outlet pipes PVC 160mm OD	12m	<u>96.00</u>
<b>Total (Materials)</b>		<b>797.00</b>
Labour	Building	300.00
	Welding	<u>200.00</u>
<b>TOTAL</b>		<b>500.00</b>

**TABLE 4: List of biogas plants**

	<b>Location</b>	<b>Type</b>	<b>Size (m<sup>3</sup>)</b>	<b>Gas Use</b>	<b>Comments</b>
1	Domboshawa Training Centre	Indian (I)	8	Cooking	Working well since 1979
2	Chishawasha	Chinese (C)	3	Cooking	Rather small
3	Chinyika School	I	8	Science laboratory refrigerator	
4	Goromonzi District offices	C	10		Probably not operational
5	Bhora Business Centre	I	8	Cooking for business	
6	St. Pauls Nutrition Village Mrewa	C	6	Cooking	
7	Rusike School Goromonzi	C	10		Finished but not yet operational
8	St. Mathias School Tsonzo	I	8	Cooking	
9	Chisangano School Wedza	I	10	Cooking	Working well
10	Kadhani Centre Mhondoro	C	8	Cooking	
11	St. Michael's School Mhondoro	I		Cooking	Has 7 drums instead of 1 gasholder
12	Nyimo Centre Sanyati	I	8		Gasholder welded on site leakage reported
13	Poshai School Shurugwi	I	8		Gasholder not welded
14	Alvord Institute Zimuto-Masvingo	I	10	Cooking	Working well
15	Mutatiri School Zimuto-Masvingo	I	10		Gasholder being welded. Not yet commissioned.

**TABLE 5 continued**

	<b>Location</b>	<b>Type</b>	<b>Size (m<sup>3</sup>)</b>	<b>Gas Use</b>	<b>Comments</b>
16	Charumbira Mudavanhu Zimuto-Masvingo	C	10		Plastering to be done. Not yet commissioned.
17	Masasa School Chivhu	C	10	Future science laboratory and domestic science.	Recently completed. Not yet commissioned.
18+	Adelaide	I C	6	Cooking	The Chinese digester is a converted septic tank used by the inhabitants.
19++	Makumbe Mission	IC		Cooking	Working well
20+	Kushinga Phikelela				Industrial generation of electricity.

**N.B.**

++ Not constructed by this Department

+ Constructed by this Department and some other agency, in most cases the owner.

## ADAPTATION OF PETROL ENGINES TO BIOGAS

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### ABSTRACT

The substitution of petrol by biogas as fuel in conventional combustion operated engines does not pose any insurmountable problems but requires adaptation works and the establishment of the procedure. This paper identifies the important factors to be taken into account in such a study.

The feasibility of producing and utilising biogas fuel in rural areas of the Sahelian zone is analysed. A 5hp motor pump suitable for small irrigation projects, adapted to run on biogas is described. Overall performance of the water pump is evaluated and compared with petrol use. As biogas is not purified (30% to 40% CO<sub>2</sub>) engine performance is lower but water pumping efficiency is still highly self sufficient for energy based only on local resources.

### INTRODUCTION

The rapid and intensive development of small irrigated plots in the Casamance and the Senegal river valleys as well as the large OMVS (Organisation de Mise en Valeur du fleuve Senegal) and OMVG (Organisation de Mise en Valeur du fleuve Gambie) schemes for the irrigation of several hundred thousand hectares in Mali, Senegal, and Mauritania, require a perfect mastery of irrigation in isolated areas where shortages in petrol and gas oil supplies are liable to occur.

The use of independent energy sources is therefore a priority for the successful development of these important agricultural valleys. The compost-biogas procedure offers great advantages in that it constitutes a minimal "energy capital" (besides producing organic fertilisers). We have studied the need for and carried out the adaptation of petrol engines to biogas. A biogas production unit and the adaptations and operating characteristics of a 5 hp motor-pump fed with biogas are described below.

### BIOGAS UNIT

The biogas unit developed is a batch system whose management and operation seems to be better suited to, and more easily carried out in Sahelian areas. It includes two digesters (diameter = 1.6m, height = 2m) in reinforced concrete, buried according to the IRAT type (Viaud 1983, 1984) (Figure 1).

In this system, the production of biogas starts a few days after the digester has been loaded and closed, then stops when fermentation ends after 50-80 days. Over this period, both the biogas production and its methane content will at first rise for approximately one week, then stabilise and finally decline.

The unit produces an average of 2 cubic metres of biogas per day. The methane content of the biogas varies with the substance used for fermentation. Since our unit was in an urban area we used wastes from Dakar's slaughter-house which were readily available on a regular basis. This also enabled us to carry out an interesting waste disposal experiment. Wastes from cattle paunches begin to

ferment very easily and quickly since the fodder has already been chewed then pre-digested for many hours before cattle were slaughtered (Petitclerc and Leclercq 1984).

Biogas analysis is performed by gas chromatography. Methane and carbon dioxide content varies in the course of the fermentation: low methane content at the very beginning of the cycle (50% CH<sub>4</sub>, 50% CO<sub>2</sub>), medium methane content in the initial and final stages (65% CH<sub>4</sub>) and high methane content in the middle of the cycle (70% CH<sub>4</sub>). It should be noted that, with the production of biogas from the wastes of cattle paunch, there is a high methane production over a major part of the cycle, since percentages above 80% of CH<sub>4</sub> have been recorded. On the other hand, cattle paunch wastes produce quite a high percentage of hydrogen sulphide. This may be due to the presence of cotton seeds in the cattle cake used for feed.

Since biogas is used to replace standard fuels, it may be useful to compare its physical and calorific properties with those of other standard fuels. These are summarised in Table 1.

### OPERATIONS WITH BIOGAS

In principle, the replacement of petrol by biogas can be done without major difficulties. However, in practice, problems will arise because the quality of biogas varies with time while those of petrol, gas oil or LPG (liquid petroleum gas) remain constant.

Under these conditions, a large number of elements and different parameters should be taken into account when adapting petrol engines to biogas (Anon 1983; Liddon 1982; Liddon and Sola 1982). These include: ignition advance; sparking plugs; carburation; compression rate; gas inlet pressure; thermal constraints; biogas methane content; corrosion; purification; moisture; dust; starting conditions; permanent or temporary operations and dual working conditions (petrol and biogas).

Taking all these elements into account, carrying out thorough analysis of their effects and interactions and optimising the parameters that can be checked and adjusted is a highly complex task and generally leads to costly solutions.

In view of conditions prevailing in the Sahel, these problems have been tackled pragmatically, and the most economical and simplest modifications have been devised to ensure valuable operations on standard, and therefore inexpensive equipment.

### MOTOR PUMP UNIT

The motor-pump unit modified for use in these tests consists of a 5 hp Brigg & Stratton petrol engine with a capacity of 206 cc (Preveral 1983). It is an air-cooled monocylinder with ignition by magnetic wheel and a rolling string starter.

The original petrol supply is provided by a "pulse-jet" membrane pump. A speed regulator is centrifugal and acts on the throttle valve. There is an oil foam model air filter. The pump fitted and delivered with the motor unit is a Grotherm centrifugal pump (L Barrere & Co builder). The body of the pump consists of a polyester mono-block. The diameters of the inlet and outlet nozzles are 1.5" (40/49mm).

The test bed is shown in figure 2. It consists of a 6 cubic metre supple tarpaulin storage unit at atmospheric pressure and a 1.2 cubic metre gasometer unit under a pressure of 5 cm of water. Before biogas is used,  $H_2S$  is removed by means of a steel wool filter. This is essential to prevent the very rapid corrosion of copper and alloy engine parts. The biogas consumption of the motor-pump is measured by means of a gasmeter suitable to measure gas delivery between 50 l/h and 3.5 m<sup>3</sup>/h.

Simulating the location of the water storage tank and variable irrigation conditions is done by means of a set of 200 l drums in which water is recycled and rate of flow measured. Manometric height can be varied from 3 to 30 metres by adjusting a bushel gate in the pump outlet.

### **ENGINE MODIFICATIONS**

The most significant adaptation on the motor-block consists of changing the original inlet pipe in order to allow for the direct injection of gas into the cylinder. This is shown in Figure 3. The intake pipe is replaced by a 3/4" elbow in galvanised metal. The original flanges are re-welded and a 3/8" pipe is brazed on the elbow so that air and biogas may flow in at right angles, thus ensuring a homogeneous air-biogas mixture. The location of the exhaust pipe has been changed by turning the outlet downwards to drain off condensation water and prevent it from flowing back into the engine when it is off.

In this engine, the ignition advance cannot be adjusted. It has been slightly advanced from 18° to 22° by increasing spark gap spacing on the primary circuit, to the detriment of sparking quality. The spark spacing of the plug which was initially 0.76mm was reduced to 0.50mm.

Biogas intake in the mixing chamber is at atmospheric pressure. An increase of 5 cm of water can be achieved by passing the biogas over the bell gasometer. This results in an increase of engine power and speed.

In the course of our first tests, the engine was started by means of petrol. Biogas was then used as soon as the engine was hot. Our subsequent tests have proved that it was possible to start the engine directly using biogas provided the intake pressure was nil (biogas at atmospheric pressure), and the biogas inlet was open slightly after the engine was started at half course of the string of the rolling-starter. The possibility of using biogas to start the engine is quite advantageous in so far as the carburettor, which is a costly engine part, can be removed.

Although an increase of the compression rate is desirable and recommended with biogas in order to increase the performance of the engine, this has not been examined because the technological design of the motor-pump would not withstand any increase in mechanical stresses.

The effect of the variation of  $CO_2$  concentration in biogas is quite significant; at the beginning of the fermentation cycle, in particular, when the gas has a low methane content, it is more difficult to start the engine. Furthermore, the rotation speed is lower than with a high methane content biogas (70% to 80%).

## EXPERIMENTAL RESULTS

In order to compare the operating conditions with petrol and biogas, we have recorded a certain number of characteristic parameters in Table 2 and Figure 4. The results presented here and the experiments described by various researchers (Leduc 1983; Lefevre 1981; Liddon 1982; Liddon and Sola 1982) suggest that the replacement of petrol by biogas is a feasible technological process. Table 2 shows that the operating parameters are very similar, except for temperature and the CO rate in exhaust fumes.

However, a strict comparison of the two supply types is difficult, since the nominal speed of a petrol-fed engine is 3000 rpm while the test was carried out at 2000 rpm. This is clear in Figure 4 which shows that the rate of flow and the manometric height of the pump "fall" completely when the pump operates at 2200 rpm. This can be improved but will add to the cost of the motor-pump.

## CONCLUSION

The present tendency is for engine builders to manufacture units that are well-suited to biogas (special alloys, ceramic parts). These units must take into account the power loss due to their fuel and the presence of harmful gases ( $H_2S$ ), but this significantly increases the cost. For the same reasons, carbon dioxide and water vapour should be removed from biogas to achieve a 20% to 50% or even 60% increase of the calorific value. However, purifiers are costly and require consumable materials for their operation.

It is also possible to supercharge the engine in order to improve the efficiency of biogas engines. Another possibility is the use of electronic ignition, which will adjust ignition advance in real time according to operating conditions, for the same purpose. Unfortunately, all these improvements involve an increase in costs and the use of sophisticated technologies with recurrent adjustment, maintenance and operating difficulties.

Under these conditions, it appears more "acceptable" and perhaps more beneficial in the short term, to lose 30% of the output with otherwise standard and reliable equipment than to manufacture more efficient yet more costly and less reliable equipment. It is therefore urgent to define the means to reach a compromise solution so that isolated and low-income rural areas can gain access to means of production.

In the case of the motor-pump unit presented here, a great degree of freedom is available with the fitting of the engine and the pump. It is therefore possible to fit out a pump suited for a 3 hp engine and a 2000 rpm speed with a 5 hp engine. Technological adaptations should be carried out along these lines if we are to meet urgent needs as rapidly as possible (Lagrange 1979).

In the middle term, the numerous teams that are tackling the problems of biogas engines will succeed in developing economical and efficient models as soon as the market is guaranteed, and research into the perfection of new prototypes has advanced.

This problem always arises with technological progress. For example, the petrol engine was made more and more reliable and efficient over the past hundred years through slight or considerable improvements. However, the research work, which in less than 5 years brought about a 20 to 30% decrease in fuel

consumption, was undertaken and carried out successfully only because external constraints were becoming unbearable. The history of the petrol engine proves that it is quite possible to develop totally reliable biogas engines which are as easy to use as the present petrol engine.

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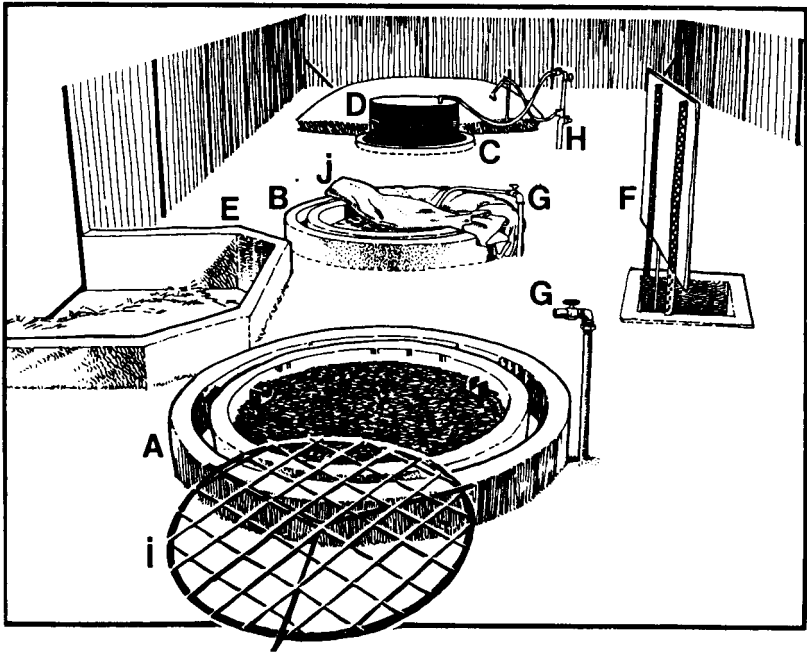
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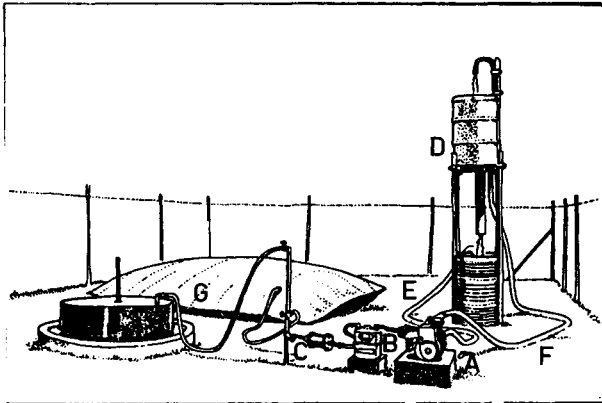
FIGURE 1: General diagram of the biogas unit

- A - digester on loading    B - empty digester    C - gasometer bell  
D - tarpaulin gasometer    E - raw material and compost storage area  
F - control panel    G,H - biogas outlet and connecting pipes  
i - stopping grid    j - airtight plastic top cover



**FIGURE 2: Test bed with simulated recycling tank and irrigation system**

- A - motor pump unit    B - gasmeter    C - H<sub>2</sub>S filter    D - drums set  
E - inlet pipe    F - outlet pipe (variable height simulation)  
G - gasometer bell and tarpaulin storage



**FIGURE 3: Assembly of the modified intake pipe**

- A - 3/4" elbow tube replacing the original inlet
- B - 3/8" biogas inlet pipe welded on the air pipe
- C - biogas vane D - air filter E - original carburettor
- F - exhaust pipe

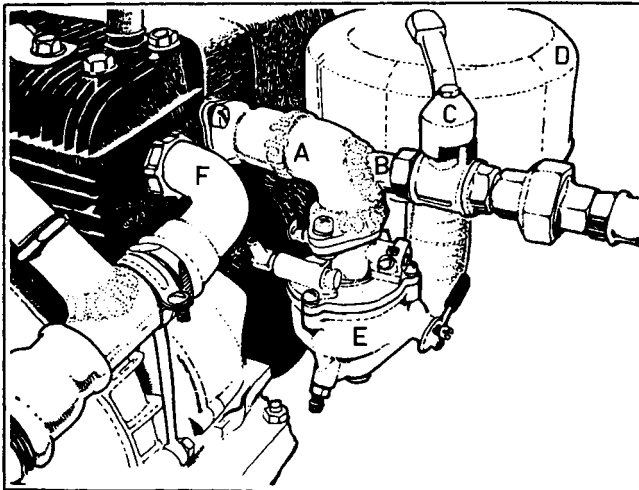
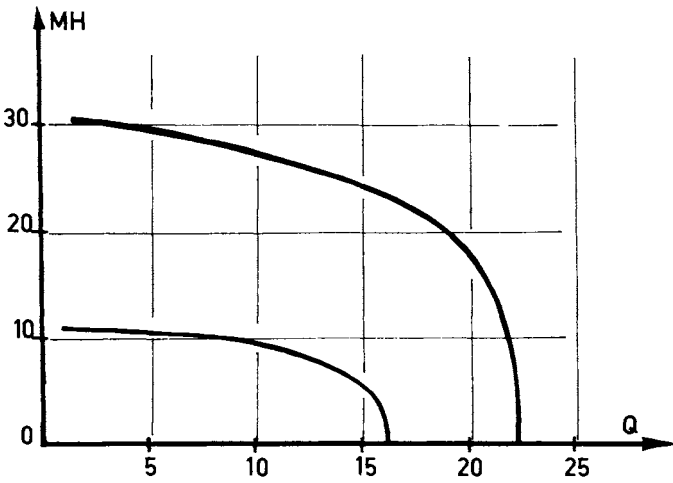


FIGURE 4: Characteristic features of the motor-pump unit  
Q water flow in cubic metre per hour and MH manometric height in metres.  
Uppercurve : petrol feed at 3000 rpm; lower, biogas feed at 2200 rpm.



**TABLE 1: Properties of biogas compared with those of petrol and gas oil. M.C.V. minimum calorific value**

<b>Biogas</b>	<b>Poor 50%</b>	<b>Medium 65%</b>	<b>High 80%</b>
Density/air	1.034	0.897	0.468
MCV kJ/m <sup>3</sup>	20,000	26,000	32,000
Equiv. m <sup>3</sup> /l petrol	0.55	0.70	0.85
Equiv. m <sup>3</sup> /l gas oil	0.50	0.60	0.70

**TABLE 2: Comparison between some parameters of petrol fed and biogas fed engine**

<b>Parameters</b>	<b>Biogas 70%</b>	<b>Petrol</b>
Rate rpm	2000	2200
Cylinder head temperature °C	130	140
Exhaust fumes temperature °C	660	570
Oil temperature °C	100	110
Ignition advance	22°	18°
Spark spacing mm	0.50	0.76
Spark gap spacing	0.60	0.50
Consumption *	1.9m <sup>3</sup> h <sup>-1</sup>	1.8 l h <sup>-1</sup>
Inlet depressure H <sub>2</sub> O centimetre	35	38
%CO exhaust fumes	0.2	5

\* This figure is coherent with Table 1 since in a centrifugal pump, the power is a function of the cubic power of rotation speed; then at 2000 rpm petrol engine consume 1.4 l h<sup>-1</sup>

## **ALTERNATIVE AUTOMOTIVE TRANSPORTATION FUELS IN THE EASTERN HEMISPHERE**

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### **ABSTRACT**

Alternative transportation fuels being used in the Eastern Hemisphere are described. These projects include: CNG usage in New Zealand; synthetic gasoline in New Zealand; SASOL diesel and alcohols in South Africa; coconut oil as a diesel extender in the Philippines; and ethanol gasoline blends in various areas. All of these alternative fuels are reviewed with respect to quality and the application problems that have been experienced.

### **INTRODUCTION**

Alcohols and other uncontentional fuels are finding extensive use in the Eastern Hemisphere. In New Zealand, Caltex Oil (NZ) Limited has a service station network selling compressed natural gas (CNG). New Zealand is also on the verge of producing gasoline from methanol. In South Africa, the SASOL plants as well as producing a mixture of alcohols which are blended into gasoline also produce synthetic diesel which is blended with petroleum derived diesel gas oil.

In this paper, alternative energy projects are discussed by product and by country. Most of these projects relate to extending gasoline supplies, but diesel fuel blends which include components from alternative sources eg coal, tar sands, shale oil, oxygenates, vegetable oils, etc, can be expected to gradually enter the markets. Perhaps the first "pure" product alternative to petroleum crude derived diesel will be remote natural gas converted to methanol and used in hybrid diesel engines in buses.

### **ETHANOL GASOLINE BLENDS**

Kenya, Philippines, Zimbabwe and Malawi are using anhydrous ethanol derived from the fermentation of sugar cane or sugar molasses in gasoline (Palmer; Unzelman et al; Sage 1984).

#### **Ethanol In Kenya**

Gasohol was launched in Kenya in May 1983 and replaced premium gasoline at oil company service stations in the Nairobi area. Commercial and government consumers were changed over to Gasohol over a period of time. The consumption of Gasohol started at 170,000 litres/day in June 1983 and has averaged 177,000 litres/day since then.

Gasohol (RON 93) is composed of: 10% volume Ethanol; 65% volume Premium Gasoline (93 RON); and 25% volume Regular Gasoline (83 RON). Ethanol (Power Alcohol as it is called in Kenya), is manufactured from molasses. The plant, a joint government/Agro Chemical Food Company venture, has a design capacity of 60,000 litres per day. Current production is approximately 20,000 litres per day.

Ethanol is transported to Nairobi by road tankers and stored at the Kenya Pipeline Company (KPC) tank farm. It is transferred to adjacent oil company depots by pipeline on a daily basis. An in-line blender, provided by the KPC, is installed before the loading rack in each depot.

The Kenya Bureau of Standards has established: a. KS03-382 Kenya Standard Specification for Power Alcohol; and b. KS03-515 Kenya Standard Specification for Gasohol. A typical Kenyan gasohol blend is shown in Table 2.

There have been very few problems. Initial problems of fuel filter blockage have now largely been resolved. At the time of introduction of Gasohol, all oil companies used thief pumps to clean out all traces of water in the underground tanks at retail outlets. Motorists were advised to drain their fuel tanks but in practice very few did so. There have been no complaints regarding vapour lock even with the high altitude and high temperatures in Nairobi. Plastic fuel lines on certain cars have elongated and it is a common site to see Ford Cortinas with sagging fuel lines almost touching the road. Claims have also been made that fuel gauges of Citroens have been affected as the floats tend to stick when the plastic fuel pipe in the fuel tank distorts. The in-line blenders provided by KPC have had problems. From time to time failures occur and then normal premium gasoline is supplied to the service stations.

The lack of operational problems is credited to a careful series of procedures laid down by oil companies to cover the quality control and handling of Gasohol at retail outlets.

### **Ethanol in the Philippines**

In the Philippines an anhydrous ethanol-gasoline blend called Alcogas is sold. The Philippines was intending to emulate Brazil and create a very large Alcogas programme. However, because of financial problems the whole programme has been reduced in scope. As of now, Alcogas is only available as regular gasoline, containing 20 vol % ethanol, and the supply area of Alcogas is limited to the sugar producing islands of Negros and Panay in the central Philippines. Premium gasoline without ethanol is also available in these areas.

Ethanol produced in alcohol distilleries adjacent to the sugar farms is bought by the Philippine National Oil Company (PNOC) and sold to the oil companies at a price which will allow the oil company to sell Alcogas at 0.25 pesos (about 1.6 US cents) per litre less than gasoline.

There was a considerable amount of customer resistance centred around the relatively small price differential between Alcogas and normal gasoline and the energy value (kilometres per litre) obtained by vehicles using Alcogas. There were so many complaints it was impossible to judge which represented genuine dissatisfaction. The price difference was adjusted slightly and the programme changed so that customers could buy premium gasoline without ethanol. While the complaints have been reduced there still remains a general dissatisfaction with Alcogas.

There is now a proposal to re-orient the Alcogas programme along an octane-enhancer route and this is being evaluated. In this approach, the levels of tetraethyl lead in gasoline would be reduced and the octane difference restored with ethanol.

### Other areas

Other areas such as Zimbabwe and Malawi are including ethanol in their gasoline. In Zimbabwe the cost of gasoline to the country represents 21% of the value of exports and the importance of reducing the foreign currency drain has outweighed production cost considerations. Since 1979, Triangle Limited, a sugar cane growing and milling company, has been the sole producer of ethanol in Zimbabwe (Wenman 1984). It sells anhydrous ethanol to the government which resells it to oil companies for blending into gasoline. Initially added at 15% volume this has now dropped to around 12%. Forty million litres of ethanol are produced per year. A second distillation plant is being evaluated for possible inclusion of ethanol in diesel.

### METHANOL

From 1983 onwards there has been a shift in methanol production from the US, Europe and Japan to resource-rich countries utilising inexpensive natural gas (Itatani 1984; Koba-yashi 1984; Strith 1984). Saudi Arabia, Soviet Union, New Zealand, Trinidad and Tobago, Bahrain, Indonesia and Malaysia are entering the market with large scale methanol plants. Methanol is likely to become a major commodity traded worldwide.

In the Eastern Hemisphere (excluding Europe), there is no large scale commercial usage of methanol as an automotive fuel either directly or blended with gasoline. However, this could change very rapidly depending on the relative economics of methanol production and transportation of the methanol to its normal markets. Currently, there are a number of methanol plants being constructed and some have already started operations. There is predicted to be a world over supply of methanol (Table 3), much of this produced in the Middle and Far East. Utilisation of methanol as an octane booster and blending additive for gasoline in Japan and possible other parts of the Eastern Hemisphere, is a logical development.

### Methanol as a transportation fuel

Methanol can be blended into gasoline or used as a neat fuel. There are drawbacks. To use neat methanol as a transportation fuel requires specifically designed vehicles and engines and a suitable fuel distribution system. Methanol is expected to be 60-65% of gasoline price on a volumetric basis. After accounting for the lower volumetric energy content of methanol, the savings in fuel cost with methanol are less than 10%. This does not provide much economic incentive to develop this application. However, neat methanol fuel markets such as centrally fueled fleets are forecast to develop in Canada, the United States and later possible other gas-rich and crude-short countries such as New Zealand, Thailand and Malaysia.

### Methanol as a diesel substitute

Although methanol has a poor cetane rating, it is feasible to use methanol in modified engines as a diesel substitute. However, tests to date indicate that mileage achieved with methanol is only 40% of diesel fuel.

Thus, methanol use as a diesel substitute will not be favourable, except perhaps in gas-rich and crude-poor regions. The first commercial uses will be in MAN or Daimler Benz buses which are currently being tested in South Africa and New Zealand (see below).

### MIXED ALCOHOL BLENDS IN SOUTH AFRICA

Sasol Fuel Alcohol (SFA) marketed over a wide area of South Africa, is derived from Sasol coal-fuels plant. It is a mixture of the following alcohols; ethanol - 70%; propanol and isopropanol - 27%; and butanol and isomers - 3%. This mixed alcohol fuel is blended into gasoline at approximately a 10% alcohol, 90% gasoline ratio.

#### Problems with mixed alcohol fuels

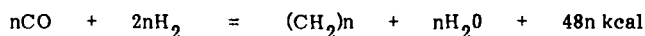
Initial problems with water contamination have been resolved by routine checks on storage tanks on a daily basis and immediately after severe rain storms. Corrosion problems were experienced, mainly in vehicle carburettors. Dry corrosion occurred as a result of chemical reaction between anhydrous alcohol and aluminium to form alkoxides which revert to aluminium oxide leading to carburettor blockages. This problem was solved by addition of a small amount of water or ethylene glycol to the fuel to inhibit the reaction. Wet corrosion occurred in certain areas of the carburettor where under the influence of low temperatures, induced by fuel evaporation, small amounts of water condense out. Electrolytic attack can occur at these sites, especially when dissimilar metals are present. This problem was cured by treating carburettors with a material referred to as Bonderite.

High speed and acceleration knock have been reported and since SFA provides negligible MON gain, a minimum MON of 85 is the current specification requirement. Gasoline/alcohol blends with RON 93 min are supplied throughout the Transvaal and Orange Free State regions. It is the only premium grade motor fuel available on the highveld which accounts for the major portion of the gasoline market in South Africa. The blend is actually produced from a hydrocarbon blendstock specifically manufactured to be mixed with SFA. The SFA content is nominally 10% but the actual ratio may vary from 8 to 12% by volume for supply reasons.

### SYNTHETIC DIESEL FUEL IN SOUTH AFRICA

Probably the greatest success for Fischer-Tropsch (F-T) technology has been the Sasol complex in South Africa. First begun in the 1950's, the complex has now completed its third construction phase. Subbituminous coal is supplied from the nearby Bosjesspuit mine.

The primary reaction in the F-T synthesis is usually written as:



Further information can be found in Haggin 1981.

### **The quality of sasol diesel and problems experienced**

The quality of the diesel, specification and typicals, are comparable to petroleum derived diesel gas oil. Nevertheless, there continue to be some problems with Sasol Secunda Diesel fuel.

For example, a recent widespread problem was experienced in the Secunda supply area in which high pressure in-line pump plungers and injector components became stuck because of fine deposit build-up. This problem is currently being investigated. The deposits were initially suspected to be of lubricating oil origin, but it now appears that an additive required for lubricity improvement may be the cause of the deposits.

Sasol now maintain that their current production of 2.2 cSt diesel need not be dosed with a lubricity additive. However, the oil industry is not yet satisfied with Sasol's test work and various field tests are proposed or under way to check the validity of Sasol's claim, and until such time pure Secunda diesel has been withdrawn from the market and a 50/50 blend of Secunda and Natref products is being marketed.

### **VEGETABLE OIL IN DIESELS**

In the Philippines, the addition of coconut oil to all diesel was mandated under a government sponsored programme called "Cocodiesel". (The programme has now been set aside because of the relatively high prices of coconut oil in world markets.) The programme required the addition of up to 5% "raw" coconut oil to diesel fuel, with the blending being done at oil company depots. The coconut oil/diesel fuel mixture developed sludges and microbial growth. This resulted in widespread complaints of clogged diesel engine fuel filters.

While the commercial cocodiesel programme has been set aside, two field test programmes have been completed which monitored the storage/handling and performance of two diesel fuel blends: a. up to 20% "dieselite" - an esterified coconut oil; and b. up to 20% "cochin" - a caustic washed coconut oil. After three to six months of observation in actual storage tanks and microbial testing and service in several fleets in various bus companies, both of these blends were considered satisfactory. But no further activity is planned because coconut oil currently has a high price on world markets.

In Malaysia, current studies are centred on the transesterification of crude palm oil (CPO) and palm oil stearin with methanol. Products produced are ethyl, isopropyl and methyl esters. A pilot project to produce palm oil diesel (methyl esters) is scheduled to commence mid 1985 with an initial production of 3000 tonnes per annum. All current engine tests (on Fiat agricultural tractors, Toyota Land Cruisers and Hino trucks) are being conducted using methyl esters purchased from Germany. With the present high price of CPO (and steady petroleum crude price), this project is expected to remain an academic exercise until at least 1990.

Considerable work on the use of vegetable oils has been done in Brazil but success has been somewhat limited. Additional information is given in Pischinger et al.

### ALCOHOLS IN DIESELS

MAN and Mercedes Benz have introduced methanol fuelled buses into South Africa and New Zealand. In these areas, and possibly others, methanol could be an attractive substitute for petroleum derived diesel, particularly if severe refinery imbalances occur (Toepel *et al*; Neitz and Chmela 1984; Bergman and Holloh). Preliminary fuel consumption figures for the Mercedes Benz buses are given Table 4.

A programme is being proposed for methanol buses in the Los angeles and the feasibility has been assessed by the US Department of Energy (Eckland).

### CONCLUSIONS

A considerable number of alternative fuels are entering the automotive fuel market in the Eastern Hemisphere. There have been some minor teething problems with the introduction of these alternative fuels, but in most cases they have been remarkably successful and trouble free.

Methanol appears to be a fuel of promise in specific countries particularly those with natural gas reserves but little oil. With lead phase downs, both methanol and ethanol may find increasing use in Caltex areas as octane enhancers.

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- TL 2003 Carbon monoxide exhaust emissions and the CNG engine. (How can a CO exhaust emissions analyser be used to get the best fuel economy?)
- TL 2004 Ignition timing and the performance of a dual-fuel CNG-petrol engine. (How should ignition timing be set?)
- TL 2005 Ignition system performance and requirements for dual fuel CNG-petrol operation. (What are the spark plug temperature and voltage requirements?)

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**TABLE 1: MTG gasoline properties**

<b>Research Octane Number</b>		
-	Unleaded	93
-	+0.84g Pb/1 (3.17 g/USG) as TEL	100
-	+0.84g Pb/1 (3.17 g/USG) as TML	99
<b>Motor Octane Number</b>		
-	Unleaded	83
-	+0.84g Pb/1 (3.17 g/USG) as TEL	91
-	+0.84g Pb/1 (3.17 g/USG) as TML	91
<b>Front-End (IBP-100° C Fraction) Research Octane Number</b>		
-	Unleaded	87
-	+0.84g Pb/1 (3.17 g/USG) as TML	95
<b>Distillation °C (°F)</b>		
-	10% Evaporated	46 (115)
-	50% Evaporated	99 (210)
-	90% Evaporated	166 (330)
-	EP	204 (400)
<b>Existent gum mg/100 ml</b>		1
<b>Sulphur % wt</b>		< 0.001
<b>Nitrogen % wt</b>		< 0.001
<b>Saturates Vol %</b>		60
<b>Olefins Vol %</b>		8
<b>Aromatics Vol %</b>		32

**TABLE 2: Typical Kenya gasohol blend**

<b>Tests</b>	<b>Regular MSR TK 306</b>	<b>Premium MSP TK 301</b>	<b>Gasohol Blend 10% ETOH 25% MSR 65% MSP</b>
Density	0.7016	0.7283	0.7249
Octane Number	83.6	93.1	93.6
<u>Distillation:-</u>			
IPB	42°C	40°C	40°C
10% Evaporated	58°C	64°C	52°C
20% Evaporated	64°C	72°C	58°C
50% Evaporated	87°C	96°C	76°C
90% Evaporated	139°C	153°C	141°C
End Point	169°C	180°C	174°C
Residue	0.8	1.0	0.6
Recovery at 70°C	28% vol	18% vol	45% vol
RVP	7.0 psi	7.1 psi	7.6 psi
Induction period	> 240	> 240	> 240
Copper strip	1a	1a	1a
Doctor Test	Negative	Negative	Negative

**TABLE 3: Operation rate projection for methanol (10,000 tons)**

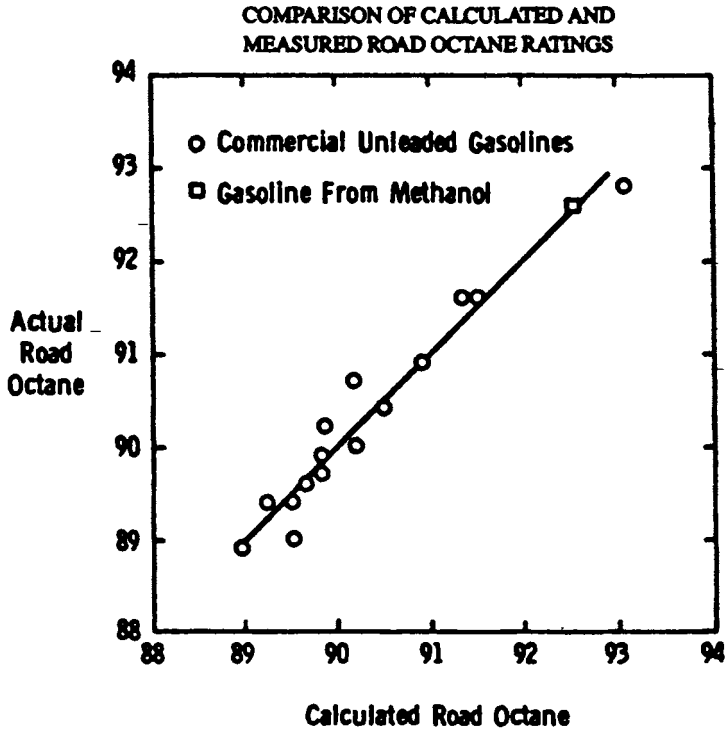
Year		1982	1983	1984	1985	1986	1987
Demand	Existing	1,056	1,077	1,099	1,121	1,143	1,166
	New*	104	109	114	120	126	132
	Total (A)	1,160	1,186	1,213	1,241	1,269	1,298
Capacity	(B)	16,166	16,583	18,334	20,954	20,954	20,954
(A)/(B)		0.72	0.72	0.66	0.59	0.61	0.62

\* For automobile fuel (including that for MTBE), SCP, other.

**TABLE 4: Results of Mercedes Benz buses running on methanol**

	<u>Auckland, NZ</u> Hilly, pure methanol	<u>Berlin, Germany</u> One route which is flat MeOH+5 to 8 vol % isopentane	<u>Pretoria, S Africa</u> One route hilly and at high altitude, pure methanol
Max Fuel Consumption litres/100 km	125.4	104.9	146.7
(Diesel Equivalent) litres/100 km	(57.0)	(47.7)	(66.7)
Min Fuel Consumption litres/100 km	95.4	91.8	114.2
(Diesel Equivalent) litres/100 km	(43.4)	(47.7)	(51.9)
<b>AVERAGE</b>	<b>108</b> <b>(49.1)</b>	<b>99.1</b> <b>(45.7)</b>	<b>128.4</b> <b>(58.4)</b>

FIGURE 1: Comparison of calculated and measured road octane ratings for commercial unleaded gasoline and gasoline from methanol



**THE POTENTIAL FOR ALCOHOL AS A FUEL IN SPARK IGNITION  
ENGINES IN TANZANIA**

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**ABSTRACT**

As a possible contribution towards the development of Tanzanian agriculture plus national fuel self sufficiency, the potential for irrigation using pumps powered by small spark ignition engines, with ethanol as the fuel, is currently being assessed at Reading University. The ethanol can be produced on a small scale from fruit market wastes and the potential from cashew fruit waste alone is estimated as 30 to 50 million l of ethanol per annum, sufficient to irrigate 15,000 to 25,000 ha.

Spark ignition engines suitable for water pumping can currently be purchased. The performance including acceptable levels of water in ethanol of a single cylinder engine run on ethanol is being investigated using the minimum of modifications possible under Tanzanian conditions. This paper outlines a system suitable for Tanzanian conditions. The initial results are promising and undergoing further investigation at Reading University and the Institute of Production Innovation (IPI).

**INTRODUCTION**

Commercial energy use in Tanzania is currently 1,200,000 tce or 60 kg tce/cap of which 90% is imported petroleum (World Bank 1981). The cost of this imported petroleum amounts to 57% of the total export bill and this percentage is rising (South 1984). Although a very heavy drain on the economy, imported fuel represents only a small fraction (8%) (derived from Mwandosya and Luhanga 1983) of the total energy use. The remainder is largely biomass in the form of wood or its derivative charcoal. The energy problem in Tanzania is not so much that of oil replacement by renewables but the per capita increase of energy availability.

Tanzania is an agricultural economy and this sector accounts for 90% of total employment. Agriculture is not a major user of commercial energy (11% of total oil imports) but its increased availability would enable greater energy input for, eg irrigation and water lifting for cattle, and result in much improved overall productivity.

Currently there is a considerable amount of biomass in the form of fruit waste which if converted to alcohol (ethanol) would provide a locally available fuel for spark ignition engines for agricultural use. This paper describes an appropriate application for use in rural areas currently under investigation at Reading University and IPI, and identifies some of the problems.

**AN OPTION FOR AGRICULTURAL DEVELOPMENT IN TANZANIA:  
SMALL SCALE IRRIGATION**

Measures taken to improve agriculture production would:

- i. Increase food production for local consumption, reducing imports and dependency on food aid.
- ii. Provide jobs and reduce urban migration.
- iii. Increase incomes from cash crops and exports.

The level of agricultural mechanisation in Tanzania is very low, and in the short term to increase this rapidly would have considerable implications for foreign exchange earnings and the requirements for petroleum imports.

The mechanisation of irrigation is an attractive initial option. Irrigation is not commonly practised in Tanzania and so could have an immediate wider scale impact at a lower cost. Irrigation projects particularly large scale schemes have not met with a great deal of success in Africa. Some primarily small scale schemes using ground water or lift irrigation have been successful (Carruthers 1983). This could prove to be more compatible with the average Tanzanian land holding, approx. 2 ha (Hyden 1980).

The power for lift irrigation can be met from a variety of sources. A number of systems based on renewable energy resources are currently under investigation. However, small spark ignition (SI) engines to drive lift pumps have been overlooked although they are being used for this purpose in some areas of the world (eg Guyana - Jordon 1984). The recent World Bank study on solar water pumping excluded SI systems after initial modelling showed the annual running costs to be too high (Halcrow 1983). This figure would include the cost of kerosene, an expensive imported fuel. However, a locally produced fuel based on biomass could possibly substantially reduce the running costs. Ethanol produced from fruit wastes could be a suitable fuel for powering such systems.

Compression ignition (CI) engines are usually chosen in preference to SI engines for such stationary uses, primarily because of low fuel costs. In addition they have a longer life-time under similar operating conditions although their initial cost is higher. However, small spark ignition engines were previously used for stationary purposes and small boat propulsion. They are lightweight, therefore more easily transportable and so could be more readily utilised for other purposes on a farm or in a village.

Engines of this type, with magneto ignition, would seem well suited for use with hydrated alcohol. Higher compression ratios could be adopted to make use of the high octane characteristics of this fuel and to compensate for the loss of power output. Either two or four stroke cycles can be used, the former has the advantage of less moving parts (no valves) which offsets to some extent the lower efficiency with respect to the four stroke cycle. Small two stroke engines with slide valves require lubrication to be added to the fuel. The Institute of Production Innovation are currently investigating the use of castor oil, a locally available vegetable oil, for such an application.

## **FEEDSTOCK**

The use of biomass as a fuel can lead to conflict between this application and that of food. Fruit waste is not subject to this criticism. It is widely available and there are no seasonal variations in supply.

Reliable estimates for the total waste resource in Tanzania are not available. However, IPI have estimated that 30 to 50 million litres of alcohol can be produced annually from cashew apples. Using the same parameters as those in the World Bank Solar Pumping Assessment Report, (Halcrow 1983) (a 2 hectare irrigated area at 7m head requiring 60 m<sup>3</sup> per day per hectare) we have estimated that this would provide sufficient fuel to irrigate 15,000 to 25,000 ha of arable farm plots.

## **ALCOHOL PRODUCTION**

Alcohol is produced by the fermentation of an aqueous sugar solution and to make a suitable fuel must be separated from the brew by distillation. Simple distillation produces 95% ethanol/5% water which can be burnt alone in an SI engine. To blend ethanol with petrol to form gasohol, however, required 99.5% ethanol which is produced by further distilling the 95% ethanol with an entrainer. Obviously the more water that can remain in the ethanol, the lower the energy and financial costs. Engines will run on high water content, as high as 50% has been reported in Brazil, but this requires substantial modification (Brinkman 1981). The scale of production can vary from over 100,000 l/day to as little as 60 l/day (National Research Council 1983).

Economies of scale make the larger systems attractive, but this requires significant sums of capital investment and a well-organised transport system to bring the feedstock to the centralised processing plant. Transport costs are also a significant contributor to the overall cost of production. These problems could be overcome by the use of a small scale system of production based on the fruit waste in market towns or fruit farms, which would be the most appropriate scale for Tanzania. There is a lack of data on appropriate materials for small systems, as well as costs and IPI are currently developing a still of 0.5/1 hour suitable for village level use.

## **ADDITIONAL USES FOR ALCOHOL AS A FUEL**

It is worth mentioning the additional fuel uses of alcohol suitable for Tanzanian application. In the rural context it could be used for cooking and lighting. It burns with a relatively smoke- and odour-free flame which is easily controlled. It ignites easily and is extinguished readily. It is possible to purchase a variety of simple stoves or they are easily fabricated. The latter would of course be attractive in terms of job creation although all the materials would need to be imported. To be used for lighting requires the addition of an illuminant since alcohol burns with a non-luminous flame. The illuminant could be a small quantity of kerosene, vegetable oil or animal fat.

Ethanol can also be used as a substitute oil-fired boiler fuel. Conversion trials for such boilers are under investigation in Brazil, (National Research Council 1983). Slight reductions in efficiency are reported but with lower NO<sub>x</sub> emissions than for fuel oil, although the aldehyde emissions are higher.

## ALCOHOL AS AN SI ENGINE FUEL

Spark ignition engines run as well on ethanol as on petrol. In terms of emissions the situation is improved with lower NO<sub>x</sub> and CO although aldehydes may be increased (Brinkman 1981). There is no need for the addition of anti-knock lead compounds. Motor engine manufacturers modify their engines to obtain the same performance from ethanol as from petrol. For stationary engines running at constant loads and speeds these modifications may be an unnecessary expense if a slight loss of power output does not create too many problems. There is evidence to suggest that many engines tend to be over-rated for their end-use. Also in Tanzania there are not sufficient numbers of skilled personnel to undertake a large programme of major modifications.

In this context we have investigated the performance of a Briggs and Stratton single cylinder 4 stroke 2.2 kW SI engine. The engine's performance is being assessed using both absolute alcohol and alcohol with various percentages of water. The percentage of water is significant in terms of the energy requirements and cost of ethanol production.

The initial engine test results have been presented in more detail elsewhere (Kawambwa 1984). Figures 1 and 2 are representative curves of the data so far obtained. The results have been in agreement with those obtained in the literature, ie a reduction in power output matched by a corresponding increase in fuel consumption as the amount of water in the ethanol increases.

The system is currently being optimised. One minor modification that could be undertaken in Tanzania would be the enlargement of the main fuel jet to give similar power output to that using gasoline.

## CONCLUSION

It would seem that there exists a potential application in Tanzania for ethanol as a fuel for driving small SI engine irrigation pump systems which would make a significant contribution to agricultural production. Work is currently in progress at Reading University to optimise the engine and pump, using only those modifications possible under Tanzanian conditions. At IPI work is being undertaken to develop an appropriate still for village level use.

## ACKNOWLEDGEMENTS

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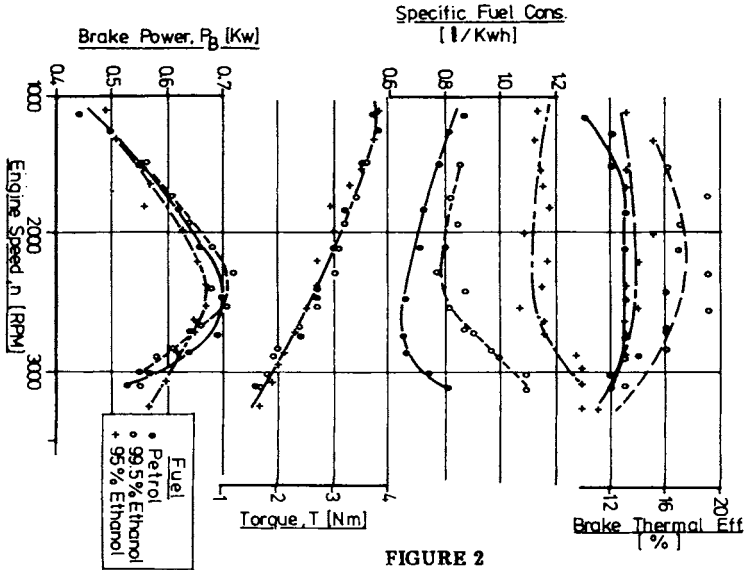
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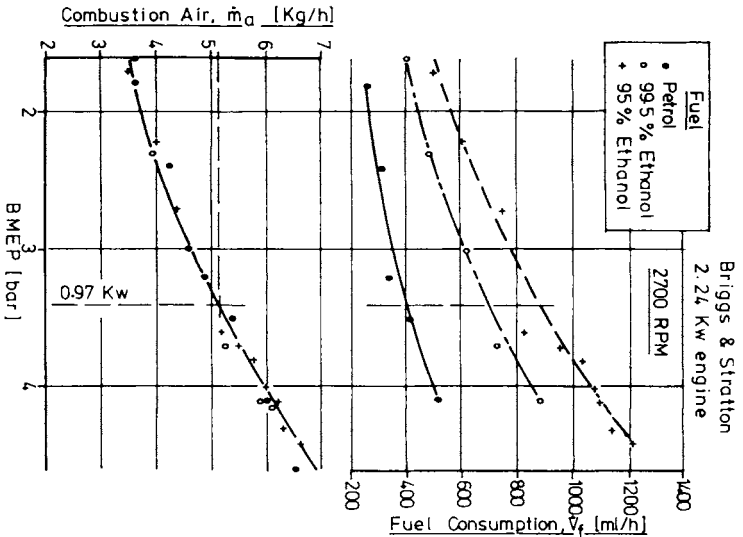
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**FIGURE 1: Constant throttle power-speed characteristic  
Throttle position 1**



**FIGURE 2**



**A CRITICAL EVALUATION OF THE PROMISE OF BIOTECHNOLOGY  
TO IMPROVE THE PRODUCTION OF RENEWABLE-ENERGY MATERIALS AND FOOD**

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Biotechnology represents the most recent applications of fundamental research in the life sciences. Its products and potential products do not usually come from the applied fields of research, such as agriculture and medicine, but rather from basic studies in reproductive physiology, immunology, molecular biology, microbial genetics, and plant physiology.

On the basis of these origins, biotechnology has several, somewhat separate, areas of product development. From immunology has come monoclonal-antibody applications of numerous types, both diagnostic and therapeutic. From molecular genetics has come gene-splicing methodology with its applications already yielding marketed products such as human insulin and promising other bacterial systems to produce important medicinal substances. And from reproductive physiology has come embryo implantation that has already allowed rapid improvements in cattle herds.

I want to focus on a further area more directly related to renewable energy technology: developments that come from basic studies in plant physiology. Much has been written about sweeping changes that will come from biotechnological research in this field. Advances such as making non-leguminous plants fix their own nitrogen and of hybridising two very different plants to form exotic, totally new, highly productive species are being given much attention. However, most of these advances - exciting though they may be - are too far off and uncertain to help us deal with the very critical problems to be faced in the next decade or two. Micropropagation is likely to yield developments in the next 10 years and is technically available to exploit in large-scale applications.

The micropropagation of plants, also called plant tissue culture, is well developed and more advances are coming rapidly. It is now possible to produce several million plants per year in a small facility that can be operated commercially at a profit and that requires only a few skilled employees. A few such facilities in Africa could produce superior plants in large numbers at low prices and could therefore greatly accelerate development. Large fast-growing plants, nitrogen-fixing species of trees, oil palms, and other plants could be propagated for renewable-energy production. Numerous other species are available for food production and other economic developments. This suggestion is not new; it has been proposed before, for example, by Lugo (1985).

For numerous species, special culture conditions have been developed and commercial production has been achieved. By selection and tissue culture of the best individual plants in a variable population, plant species known to grow well in Africa could be introduced in new localities quickly, cheaply and effectively.

On just a few acres of ground, a tissue culture facility can produce four million plants per year. Selected cuttings are first established in primary, sterile cultures in test tubes or small bottles and allowed to grow under the influence of hormones in the culture medium to maximise branching. About 20 branches are produced in a culture vessel and each branch is cut free and re-cultured in another tube to produce 20 more plants, all of which are sterile and have identical genetic and growth characteristics. Plants at this stage do not have

and do not need roots. One room for sterile inoculation of the culture tubes would serve a whole facility. Tubes are then placed in growth rooms, three of which are sufficient. Each growth room should measure about three by six metres. In most cases, these tiny plants can be immediately placed in soil where they will form roots in a few weeks if kept very moist and grow to sizes that can be planted in low-cost greenhouses or in the field if the weather is good.

A facility of this nature is operated by a for-profit corporation, named Phyton Technologies in Tennessee. It employs five skilled managers, but otherwise uses an unskilled, low-cost workforce of about 50. Other than for standard sterilisers and sterile inoculating hoods, no expensive equipment is used.

Prices are very low for such plants, and the quality is high because they have been started without any pathogenic fungi or bacteria present to slow their growth. But more importantly, the quality of product is uniform, since the original stock selected for culture was the very best plants and only continuing growth of somatic cells has been allowed.

The specific activity for Africa would be a superior tree programme. The US Forest Service has operated such a programme for many years and has resulted in large forest stands of uniform and high quality trees. A programme in Africa would have the advantage over such an older programme, in that it could progress more quickly by using the methods of micropopagation. It is possible to project that within five to 10 years large plantings of trees for fuelwood, fibre, and wind breaks could be well established and, in a few cases, be nearing harvest.

The second consideration is not a technical matter. Frequently renewable resources are not developed because people do not see profitable enough economic incentives. A recent biomass-energy publication in the United States (National Wood Energy Association 1985) states that with 9% of the energy used in the US coming from renewable energy sources this represents a higher input of energy than is produced from nuclear sources. The report is designed to have political influence. It cites government tax and budget policy decisions that are disadvantageous to this area. While such a campaign does not directly affect African nations, it is important since it shows first, that there is a voice speaking in the US for small renewable-energy businesses and second, that that voice is being used for political influence on US public and corporate policies.

Thus I urge you to champion, in your own countries, the causes of renewable-energy businesses. The propagation of trees by the methods described above can be one such business enterprise. The establishment of small businesses is itself a worthy cause. In the US, for example, large businesses are not in general contributing new jobs. These come from new companies in the US and that is undoubtedly true in African countries too.

In summary, biotechnology has great potential to contribute to development in Africa in the foreseeable future. Many different species can be propagated with applications for renewable-energy and food production. It will be important to gain governmental and public support for biotechnological research and product development. This should emphasise, in particular, the establishment of new business enterprises.

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## Renewable Energy Development in Africa

### Proceedings of the International Conference on Research and Development of Renewable Energy Technologies in Africa

The first international conference on research and development of renewable energy in Africa was held in Mauritius from the 25-29 March 1985.

The Conference, held under the auspices of the African Energy Programme of the Commonwealth Science Council, was attended by 100 scientists, researchers, policy makers from 30 countries, and representatives of international organisations.

The Conference had three main objectives:

- \* to report the results of research projects on renewable energy technologies in Africa covering both the activities of the African Energy Programme and other institutions/agencies;
- \* to provide an opportunity for international exchange of research ideas and information between African scientists and colleagues from elsewhere;
- \* to provide a forum for scientists and potential donors to explore modalities for future collaboration on energy research and development in Africa.

Over 70 technical papers were presented on research and development programmes in Africa and contributions from international collaborators. These papers, presented under four generic themes, have been edited and produced into a 2-volume set of conference proceedings. The proceedings provide the most comprehensive single assembly of renewable energy research progress in Africa.

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