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COMPARATIVE STUDY OF BOX-TYPE SOLAR COOKERS IN NICARAGUA

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Abstract—Two box-type solar ovens were performance tested under various measured solar intensity conditions. One oven was the Kerr-Cole Eco-cooker assembled from a prefabricated cardboard kit. The second model was made of plywood and involved more elaborate construction. We adopt a simple parameter-free index to aid in the comparison of oven performance. Unlike other oven test procedures this index emphasizes the dynamic cooking capability of the ovens. We find that despite a substantially reduced thermal capacity the cardboard oven exhibited a maximum temperature and sufficient thermal stability for cooking similar quantities of food to that of the plywood model. The prospects for large scale introduction of the ovens in Nicaragua is evaluated in terms of local needs and interest.

INTRODUCTION

There has been considerable recent interest [1–3] in the applicability of solar ovens in developing, particularly equatorial, countries. Solar ovens of various constructions [4] have been shown to effectively cook many foods and seem particularly appealing as an energy efficient alternative in areas where wood or fossil fuels are time consuming to collect, expensive, or simply unobtainable. The economics, versatility, durability, and cultural appeal of the devices are sometimes overlooked considerations but are tremendously important issues that must be considered in the potential large-scale adoption of this appropriate technology device.

In this article we consider the performance of two simple box-type solar ovens that have been introduced by one of us (W.F.L.) in Nicaragua and subsequently constructed and utilized in several agricultural and light-industry collectives. (For a review of the status of alternate energy, particularly solar, technology in Nicaragua see [5–8] and references therein.) The relative performance of the two oven types is compared in side by side experiments. One of the goals of this study is to determine if the added expense in materials and construction time required for the plywood model is necessary for performance reasons, for durability requirements or because of the preference of the people who use the ovens. The ovens do differ significantly in the technical skills, materials, and time commitment required for construction.

We begin with a discussion of the design criteria used in choosing the oven geometry and construction materials. We then describe the measurement methods used in the oven comparison tests and report the results. The experiments were conducted during the rainy season to test performance under the most adverse conditions that will be faced in actual oven use. The ovens are rectangular glass top boxes measuring roughly 1′ by 2′ by 2′ that under bright sun can bring a 2 liter quantity of water from ambient to boiling temperature in under half an hour.

To quantify such "cooking" experiments a simple, parameter-free, performance index is described and computed for each oven under a variety of solar intensity conditions. We suggest the adoption of such a standard performance criteria for all passive solar architecture devices so that efficiency comparisons can be readily made. Previously introduced thermal performance tests have been used to measure the *static*

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efficiency or load capacity of box-type ovens [2]. We are primarily interested in the usefulness of the ovens in *real* cooking situations that exist, for example, in rural settings in developing countries. The performance index introduced here reflects this concern by quantifying the cooking capacity of the oven under the *dynamic* conditions of prolonged use during changing atmospheric (temperature, cloud cover and solar angle) conditions. We conclude with a discussion of the relative merits of the two oven types based on their performance, ease and expense of construction, and expressed preference of the groups of Nicaraguans involved in the project.

SIZE AND SHAPE CONSIDERATIONS

The oven performance is based on the fact that the input solar energy enters through the top glass area and is lost as heat, radiation and conduction through all six sides of the box. The ovens, basically simple boxes with glass tops, are described in the following section. Thus, one would like to maximize the top area relative to the other five sides. The optimum ratio of top area to that of the sides and bottom, with altitude fixed at unity, is obtained by a circular oven. Consider the ratio:

$$R_{\text{circle}} = \frac{\text{top area}}{\text{sides} + \text{top} + \text{bottom area}}$$

$$= \frac{\pi r^2}{2\pi rh + 2\pi r^2} = \frac{r}{2h + 2r}. \tag{1}$$

For $r = h = 1$ this yields a ratio $R_{\text{circle}} = 0.25$. The difficulty in constructing circular (disc) ovens is obviously prohibitive (not to mention inefficient when used with rectangular cooking pots) and we therefore confine our discussion to box shape ovens. For a square box with the same area as in the circular case, i.e. $l^2 = \pi r^2$, the ratio R_{box} is,

$$R_{\text{box}} = \frac{l^2}{4lh + 2l^2} = \frac{l}{4h + 2l}$$

$$= \frac{\sqrt{\pi r}}{4h + 2\sqrt{\pi r}}. \tag{2}$$

For $r = h = 1$ the ratio R_{box} is 0.235 which is only 8% less than in the circular case. Rectangular ovens are essentially no less efficient than square ones. For a box with a 2 : 1 aspect ratio we have:

$$R_{\text{rect}} = \frac{2l^2}{6lh + 4l^2} = \frac{l}{3h + 2l}. \tag{3}$$

Substituting $2l^2 = \pi r^2$ into the ratio, R_{rect}, and again using $r = h = 1$ we obtain a ratio of 0.227.

In practice the greatest energy loss from a functioning oven is from the glass to wood or glass to cardboard interface around the top edge. This is due both to construction effects and the greater thermal conductivity of glass to that of wood. A square oven minimizes "glass perimeter" length and is thus slightly optimal over a rectangular box. We are currently optimizing the oven design based on the results of Nandwani's [3] study of the thermal capacity and efficiency of box-type solar cookers.

The altitude of the box should be as small as possible commensurate with the height of the cooking containers to be used. This follows directly from the previous heat loss argument and is furthered by the fact that, for solar positions far from zenith, the box side facing the sun will cast a shadow directly on the black cooking plate. This acts to reduce the plate area that is collecting direct solar radiation and permits a fraction of the plate to radiatively cool.

It is for these reasons that we chose the nearly square, shallow, oven designs for study. In any real-world application, ease of construction and operation are of paramount importance, and rectangular ovens are certainly superior in these respects as well.

OVEN DESCRIPTIONS

The two ovens chosen for this study are similar in concept but differ in ways that make performance comparisons significant. The ovens are nearly square boxes with glass tops to transmit the sunlight and reflecting walls to redirect the reflected sunlight to the blackened, absorbing, metal cooking container placed in the oven. The glass is nearly opaque to the internally re-radiated infrared radiation (the greenhouse effect). Sealing of the corners to prevent air flow and insulation in the sides and bottom permit reasonable cooking temperatures to develop within the oven (see the Results section for details).

This simple design has the advantage of ease of construction, use of simple materials, low cost, and convenient operation. The addition of one or two plane reflectors increases the obtained oven temperature, particularly at low sun angles, while requiring very little additional construction or adjustment during cooking hours (especially at tropical latitudes). Both ovens utilize single additional reflector panels that doubled as protective lids when the ovens were not in use. These features make the simple box cooker far more appropriate for tropical use than the high-tech solar cooking concentrators that have not proven successful in past attempts to introduce ovens to equatorial countries [8].

The first oven we studied (hereafter KC) is made almost entirely of construction quality corrugated cardboard of approximately $\frac{1}{8}$ inch thickness. It was assembled from a prefabricated kit according to the instructions provided by the manufacturer (Kerr-Cole Solar, P.O. Box 27417, Tempe, AZ 85282, U.S.A.) except for the addition of 2″ of styrofoam insulation on the oven bottom. The overall dimensions are 11″ by 25″ by 29″, the top glass opening is 18″ by 22″, and the inside black floor plate is 17″ by 22″ leaving approximately 3″ for wall and bottom insulation. The black metal sheet is 0.3 mm thick aluminum. The sides consist of seven thicknesses of cardboard and a diagonal space bar to create an insulating air pocket. The inside available cooking space is $8\frac{1}{2}$″ deep under a single pane of common window glass. The reflector, a 21.5″ by 28″ cardboard sheet, is faced with aluminum foil as are all the inside surfaces. Photographs of both ovens can be found in Fig. 1 (KC oven at left).

Food is introduced into the oven by lifting the top assembly (lid, glass, and reflector) off the oven. In both ovens blackened cooking pots are placed directly on the blackened metal cooking plate. As mentioned previously the plate was found to maintain a highly uniform temperature even when part of the surface is under shadow. Heating of the food containers is therefore primarily by direct conduction from the cooking surface and also by conduction from the air heated above the sheet and direct absorption of radiation by the pots themselves. Re-radiation from the oven is minimized by appropriate choice of the type of glass, the thickness of the glass and in the wooden oven, by the use of two planes of glass.

It is estimated that one person starting from uncut cardboard supplies can construct an oven of this type in one day. A time consuming aspect of the fabrication process is aluminizing all the interior cardboard surfaces to reduce radiation losses. Fourteen different pieces of cardboard in nine different sizes are required for construction.

The second oven (hereafter N) is based on a design that has been studied by Nandwani [3] at the National University of Costa Rica and modified by W.F.L. in two years of field use in Guatemala and Nicaragua. It is made primarily of half-inch thick plywood and measures 10.5″ by 28.5″ by 33″ and utilizes two planes of glass separated by a 2 cm space. The outer plane of glass forms the box top and measures 26″ by 31″ while the inner plane rests on the top of the interior

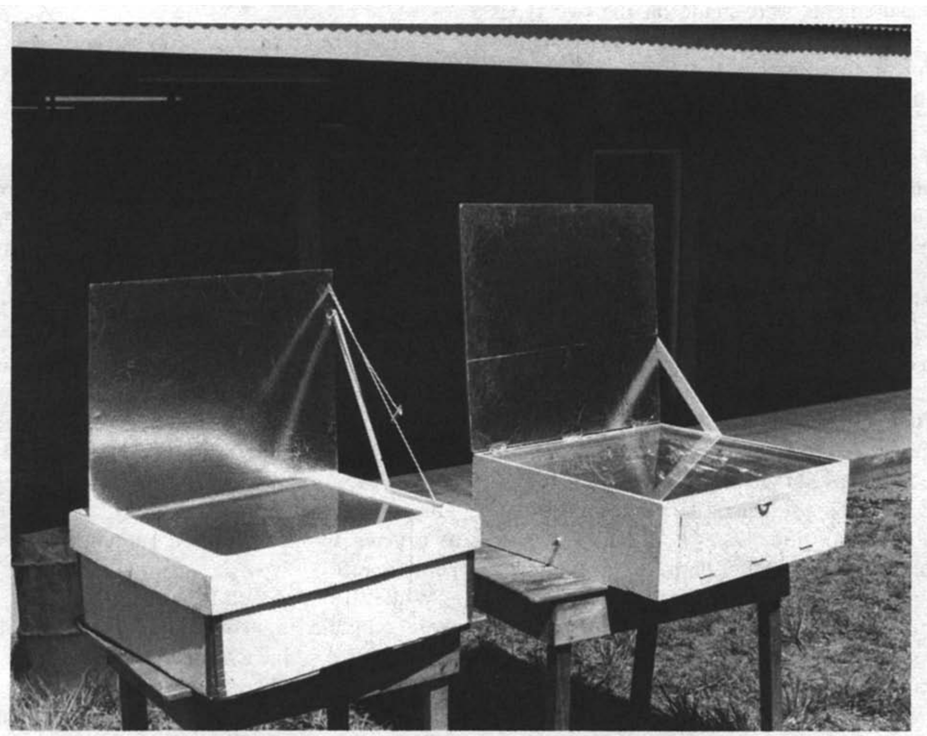

Fig. 1. The KC (cardboard oven on left) and N (plywood oven on right) ovens discussed in the text. The top of the KC oven is removed for access to the cooking space while the door on the front is used to enter the N oven. The oven lids are aluminized and can be oriented for maximum indirect solar energy collection. Photograph taken at UNAN Department of Physics, Managua, Nicaragua.

insulating walls and measures 24.5″ by 28″. The inside black plate (floor) is the same size as the smaller glass sheet and is 6″ below the glass (resulting in a shallower cooking space than the Kerr-Cole oven). There are 2″ of fiberglass insulation in the oven walls and 3″ under the aluminum floor (0.75″ thick). The cooking pots (also painted black for improved heat absorption) are placed directly on the metal plate and heat primarily by conduction. The inside surface of the oven is aluminized.

Food is introduced through an insulated hinged door in the front wall of the oven. The perimeter of this door contributed significantly to heat loss, however this can be reduced by careful workmanship and by locating the frame inside the door to cover the cracks.

Inexperienced workers can construct these ovens at the rate of about one per week per person. In practice both ovens are often made by groups under the guidance of an experienced carpenter which reduces the construction time considerably.

MEASUREMENT METHODS

In September, October and December of 1988 side by side measurements were made on the two types of passive solar ovens comparing their performance under identical environmental conditions. The fact that the rainy season was in progress during our tests did not greatly alter the maximum ambient temperature but did significantly reduce the intervals of uninterrupted sunshine that we received. The mean ambient temperature in western Nicaragua exhibits a 5 to 10°C increase during the dry season and the cloud coverage is significantly reduced during the daylight hours during this season [9]. We found the cloud coverage to be the more significant of the two factors and we can expect an increase from the roughly 140°C peak values we observed during the rainy season to peak plate temperatures in the 160–180°C regime during the summer. In rainy or dry season, therefore, the ovens have thus proved their worth as cooking devices as they can maintain a sufficient temperature for boiling type food preparation.

The data exhibited greater than 20% minute by minute variations in solar intensity due to the intermittent cloud cover characteristic of the tropical rainy season [10]. We see in the oven comparison data (Figs 2–4) that the temperature fluctuations were averaged out by the thermal capacity of the ovens and did not greatly alter the cooking capabilities of the ovens. The study was carried out at the Estación Actinometrica "VADSTENA" of the University of Central America (U.C.A.) in Managua, Nicaragua, to take advantage of the accurate solar intensity data regularly recorded there. The station, on the flat roof of a classroom building, is at latitude 12°01′, longitude 86°25′ and elevation 132 m above sea level.

We recorded the time required for both ovens to heat from ambient to peak temperature values and the temperature stability with and without a thermal load in side by side comparisons under measured solar intensity conditions. An equal volume of water in a blackened cooking pot was placed in each oven to simulate a volume of food to be cooked.

The temperature measurements were collected from zincrumel metal electrodes mounted near the edge of the metal heating plates that, like the cooking pots, are in direct thermal contact with the cooking vessels. This positioning was necessary due to the electrode geometry, however, spot measurements taken away from the walls showed less than a 5°C variation across the iron plate. This uniformity is not surprising due to the high conductivity of the metal sheet. Direct and diffuse solar intensity data was recorded concurrently with the oven and ambient temperature data.

PERFORMANCE INDEX

A number of researchers are currently constructing and testing solar ovens [1, 3, 5, 12] of various designs and materials. A standardized measure that is independent of oven parameters and solar intensity information is needed for direct comparison of oven performance. Nandwani [3], for example, has determined the efficiency of ovens of various design specifications and formulated models of thermal conduction, radiation and re-radiation effects in the box cookers. Mullick *et al.* [2] have provided a series of test procedures for rating the performance of box-type solar cookers. The simplest algorithm explored in their study is a straightforward difference measure of the achieved oven temperature to the ambient value. The insulation on a horizontal oven surface, H, is used to normalize the index: $I = (T_{\text{oven}} - T_{\text{amb}})/H$. This index is useful in rating the efficiency of the oven at a given moment or as a running index of oven performance.

While this approach is useful, we suggest an even more simplified system where only a knowledge of the oven and ambient temperature is utilized without reference to the thermal characteristics of any particular part of the cooker. In this way the resulting index reflects the ability of the oven to maintain a cooking temperature irrespective of the geometry, materials or details of the construction. Furthermore ambient and peak temperature data for the ovens

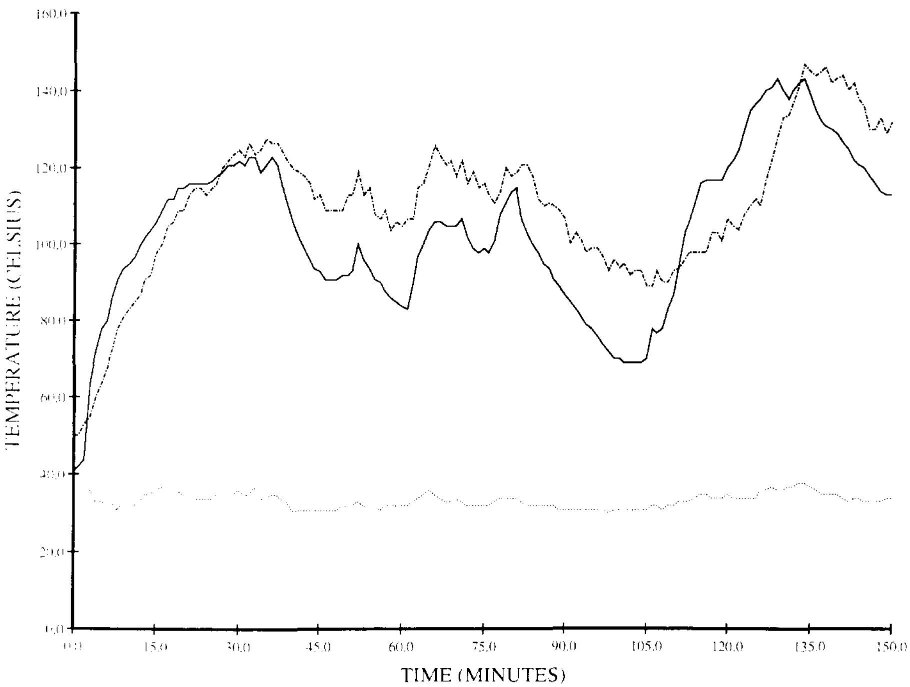

Fig. 2. Case I: heating curves for the two ovens. The light dotted curve is the ambient temperature, the solid line is for the KC oven and the dashed line corresponds to the N oven. After the initial heating phase the plywood (N) oven maintained a more uniform and higher plate temperature. The temperature fluctuations are due to changing cloud cover during the experiment. The first 30 minutes of the plot, during which time the oven was heating up, are assigned to the *changing* phase of the PI calculation (see Table 1) while the remaining 2 hours are considered to be *stable*, or thermally equilibrated.

during prolonged field use is of great value in analysis of oven effectiveness and very simple equipment is sufficient for this data to be recorded by the people using these ovens on a day-to-day basis. We have adopted the parameter free index:

$$PI = \frac{\int_{t_0}^{t_f} [T_{\text{oven}} - T_{\text{amb}}]\,dt}{\int_{t_0}^{t_f} T_{\text{amb}}\,dt}, \tag{4}$$

where T_{amb} is the ambient atmospheric temperature. This index simply normalizes the total integrated heating (performance) achieved by the oven relative to that of the ambient environment. We find this simple index more useful than more sophisticated models that require the calculation of solar radiation parameters (see, for example [3] and [10]; and see [11] for basic engineering principles for passive solar devices). For an oven that maintains a constant 100°C temperature for an hour while the ambient temperature is 35°C the PI would be:

$$PI = \frac{\int_{t=0}^{t=60} [65^\circ\text{C}]\,dt}{\int_{t=0}^{t=60} [35^\circ\text{C}]\,dt} = 1.86, \tag{5}$$

with time in minutes. In the following sections we use this index to compare the heating times, thermal stability, and thermal capacity while cooking foods of the two oven types.

At the VADSTENA solar measurement station direct and diffuse solar irradiance data was available from detectors situated next to the ovens. We were thus able to evaluate the usefulness of the PI as an indicator of oven performance to that obtained by calculating the oven efficiency by more traditional techniques.

RESULTS

The principal tests we used to evaluate the performance of the ovens were:

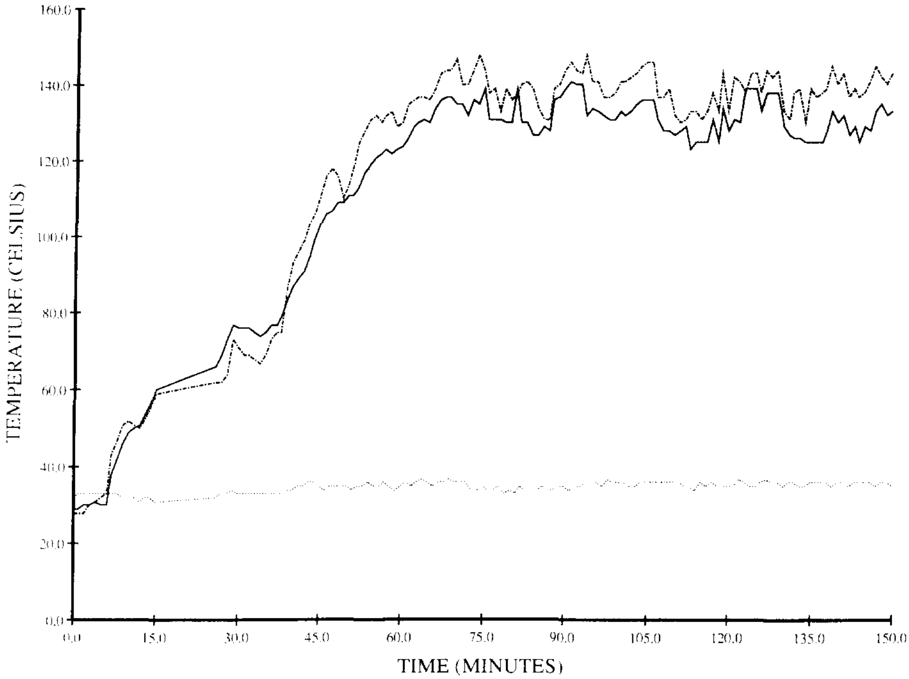

Fig. 3. Case II: heating curves for ovens with a 2.0 liter thermal load. The legend is as in Fig. 2 (dotted is ambient, solid is KC, and dashed is N). The first 60 min of the plot are assigned to the *changing* phase of the PI calculation (see Table 1) while the remaining 2 hours are considered to be *stable*. Again, see Table 1.

(i) empty oven heating times and subsequent temperature stability during intermixed clear and cloudy conditions,
(ii) heating and subsequent temperature stability comparison with 2.0 liter water thermal loads in each oven, and
(iii) cooling curves for unloaded ovens, initially in direct sunlight, that were covered and allowed to cool.

The data from these measurements are presented in Figs 2–4 and the associated *PI* comparison in Table 1. Tests (i) and (ii) were performed for straightforward comparison of the temperature stability and actual cooking performance of the ovens. Test (iii) provided an unambiguous comparison of the thermal capacity, as measured as heat retention in the absence of incident solar energy, of each oven. We will discuss these tests in order in the following paragraphs. In each plot of oven temperature the ambient (atmospheric) temperature is plotted as a thin dotted line, while the KC and plywood oven values are plotted as solid and dashed curves, respectively.

The unloaded oven tests (i) demonstrate the obvious advantages and disadvantages of the cheaper cardboard (KC) oven: small thermal capacity. The KC oven heated slightly faster than the plywood oven (see Fig. 2: time 0–30 min). While rapidity of heating is certainly beneficial, cooking occurs during a prolonged time in passive ovens and over the 2 hours of oven operation (Fig. 2: time 30–150 min) the plywood oven maintained a 10 to 20% higher operating temperature and exhibited a somewhat greater resistance to temperature fluctuations induced by changing cloud cover. During test (i) the cloud cover was intermittent and the highest temperature recorded (for the plywood oven) was 158°C.

In Fig. 3 we present heating curves for the KC and plywood ovens, each of which contained a pot of 2.0 liters of water which we utilized as the thermal "cooking" load. This test (ii) was intended to simulate actual cooking conditions with a loaded oven. The principal difference from case (i) is the increased time required for the ovens to reach a reasonable cooking temperature. For example, the unloaded ovens required approximately 30 min to reach 120°C, while the loaded ovens required roughly an hour. Again we see that the superior thermal capacity of the plywood oven resulted in a somewhat higher maximum temperature and temperature stability during cloudy

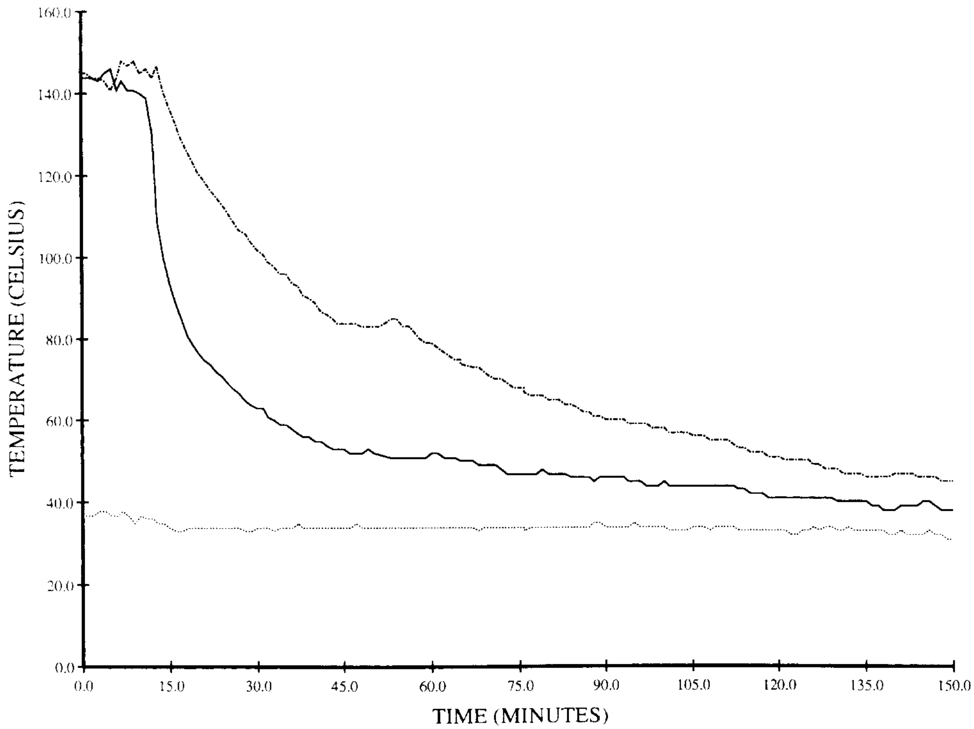

Fig. 4. Case III: cooling curves for unloaded (empty) ovens. The legend is as in Fig. 2 (dotted is ambient, solid is KC, and dashed is N). The data, beginning when the oven was removed from sunlight is used in calculating the *changing* PI as indicated in Table 1.

Table 1. Performance Index (PI) comparison for the cardboard (KC) and plywood (N) ovens under the three test cases (i–iii) as discussed in the text. For each test case two PI values are given for each oven. The first, or *changing*, value is that PI during the *heating* (cases i, ii) or cooling (case iii) phases. The second PI for each oven, the *stable* value is that obtained *after* heating in cases (i) and (ii). The maximum PI obtained in any 15 min interval was 2.77 (oven N, case ii). See Figs 2–4 for the temperature vs. time data for each of the three cases. The data was collected and binned in one minute intervals for calculation

CASE	PERFORMANCE INDEX (PI)			
	Kerr-Cole Oven		Nicaragua Oven	
	T changing	T stable	T changing	T stable
CASE 1: Heating Empty Oven	1.87	2.09	1.81	2.43
CASE 2: Heating Loaded Oven	1.25	2.45	1.29	2.77
CASE 3: Cooling Empty Oven	0.77	—	1.46	—

periods. Measurement of the actual water temperature in the cooking vessels was also sampled at various times during loaded oven tests. We found that once the ovens achieved their peak values (Fig. 3; after 45 60 min) the pot temperature was within 5°C of the plate temperature. This result further justifys the performance index used in this paper as a reasonable measure of oven performance.

Both ovens performed comparably and maintained the "load" at about the same value for the duration of the test. In addition we performed a number of cooking demonstrations in local collectives in which rice, cake and other foods were prepared during the roughly one hour introductory lecture and eaten by the audience after the session was completed.

We have included Fig. 4 to highlight the difference in thermal capacity of the two ovens. In this case (iii) the ovens were both removed from direct sunlight at the same time and allowed to cool. The plywood oven maintained a significantly higher temperature during this time that obviously reflects the greater thermal capacity of the plywood as well as the use of two planes of glass. During the first hour of cooling the *PI* of the plywood oven was 1.46 while that of the KC oven was 0.77 (see Table 1 for complete oven comparison statistics).

A summary of the performance indices for both ovens during the test cases (i)–(iii) is presented in Table 1. We found no appreciable difference in the heating time required for either oven while the plywood oven maintained a 10 to 15% higher temperature during heating trials (cases i and ii) and a significantly higher *PI* during cooling (case iii).

CONCLUSIONS

The data we have presented, along with actual cooking experience in the solar ovens, indicates that both ovens in this test perform quite efficiently under both partially obscured and clear sun conditions.

Both ovens have demonstrated their use in day-to-day cooking as a useful addition to the food preparation devices in an equatorial setting or fuel scarce environment. The primary function of either the plywood or wood oven is in the heating or boiling of rice, beans or other such foodstuffs. We have shown that *both* ovens can maintain a large thermal load at a sufficient temperature to transfer to the food the 4.2 kJ/kg °C necessary for boiling purposes.

The advantage of the plywood oven emerges when partly cloudy and unpredictable precipitation conditions prevail. The higher peak and more uniform temperatures obtained in the plywood oven indicate that there will be days during the rainy season when a meal placed in the oven will cook while in the cardboard oven a longer cooking time may be required. For foods such as beans that are currently boiled *overnight* on a gas stove the increased cooking time required in the KC oven may prove too much of a drawback in Central America—particularly if the ovens are to be used for most of the year. This is especially true in the relatively common tropical condition of morning sun, midday showers, and sun again late in the afternoon. An advantage of the plywood oven is that it can be left unattended and survive the midday showers. The disadvantages of the oven are the relative high cost of construction materials and the difficulty and time required for the process.

The Kerr-Cole Solar Oven is highly efficient, light, and easy to use. It is of low cost and the ease of construction provides a tremendous advantage for large-scale introduction of this very appropriate technology. Given the similarity in performance of the two ovens in actual heating tests (case ii and demonstrations in Nicaraguan agricultural collectives) we would expect KC ovens to be selected for large-scale introduction of solar oven technology to a country such as Nicaragua. The simplicity and low cost (in materials and construction time) of the cardboard ovens might be so great that replacement of the occasional rain soaked cardboard cooker make it the superior choice for some areas. For introduction to sub-Saharan climates the lack of rain altogether and scarcity of cooking fuels may make the KC oven, perhaps introduced on a large scale as a development project, a tremendous economic boom. The manufacturer of the KC oven also produces a larger Patio Solar Box Cooker and distributes guidelines for "weatherguarding", or adding a plywood outer box for their ovens.

Native Nicaraguan craftsmen (primarily men) and cooks (primarily women), however, uniformly preferred the more substantial appearance and durability of the wooden ovens and always selected it for construction during the demonstration workshops we conducted in Nicaragua. A number of agricultural collectives were even interested in constructing and marketing the plywood solar ovens to neighboring combines.

The usefulness of passive solar ovens is by no means confined to the preparation of food. Ciochetti and Metcalf [12], for example, have studied the temperature and duration of heating required to pasturize contaminated liquids. They find that bringing water to 60°C is sufficient to decontaminate California river water. Field tests in lowland watersheds in Guatemala, Nicaragua and Costa Rica are planned for 1989 [13]. In our cast study (ii) we easily obtained temperatures well over 100°C in 2.0 liter water samples. In-expensive temperature indicators could be distributed with the oven kits along with instructions for using the ovens for water decontamination. In a future article we will discuss a number of applications for the ovens as well as reporting on the acceptance of the ovens in a number of communities on the Pacific Coast of Nicaragua and in Guatemala [13].

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