Development of a Comparative Framework for Evaluating the Performance of Solar Cooking Devices:

Combining Ergonomic, Thermal, and Qualitative Data into an Understandable, Reproducible, and Rigorous Testing Method

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Abstract

The need to cook food for nourishment is fundamental to nearly every society and requires the expenditure of energy in some form. Solar energy can be harnessed to meet this need without the environmental and health problems associated with most other fuels. There are a wide variety of devices designed to capture the sun's energy and harness it for cooking food, unfortunately, it is often difficult to compare these devices to one another. This is due mainly to the lack of a testing standard capable of normalizing rigorous measured data to environmental conditions, which vary heavily with site and time of year.

There are three major testing standards currently in use, globally. These existing standards were examined and compared. Though many strong points were noticed, there was clear room for improvement. A new testing standard is proposed that builds upon the strengths of existing standards while addressing some of their perceived weaknesses. This new standard incorporates a number of figures of merit drawn from thermal performance of the solar cooker, which are normalized to a set of standard environmental conditions. Observations based on ergonomics and safety are also given consideration. It is hoped that this new standard will bridge the gaps between existing standards and be considered by the international community as a viable, universal testing framework for evaluating the performance of solar cookers.

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1. 0 Introduction

The use of solar energy to cook food presents a viable alternative to the use of fuelwood, kerosene, and other fuels traditionally used in developing countries for the purpose of preparing food. While certainly, solar cookers cannot entirely halt the use of combustible fuels for food preparation, it can be shown that properly applied, solar cooking can be used as an effective mitigation tool with regards to global climate change, deforestation, and economic debasement of the world's poorest people.

1.1 Social and Economic Drawbacks of Biomass Fuel Sources

In many regions of the world, the primary source of energy is derived from biomass. This biomass can take the form of wood (either foraged or directly harvested), animal wastes, crop residue, or other similarly burnable materials(OTA, 1992). The energy content of these fuels varies but they all share in common their relatively low caloric content, necessitating large usage volumes for a relatively small amount of delivered energy. Also in common, each represents a significant threat to ecosystem and human health if overused.

The task of gathering fuelwood falls almost entirely on women and children. It is not uncommon for residents of particularly sparse regions to spend more than 90 hours per month harvesting fuelwood (Tucker, 1999).

Furthermore, UNICEF and other international aid groups have identified significant health problems associated with the use of indoor cooking fires. An estimated 5 million children in the developing world die each year from respiratory ailments (Tucker, 1999) and a further 5 million are estimated to die from complications associated with contaminated drinking water. These figures are staggering in their implications and they are both, at least partially, solvable using solar cooking technology. (Addison, Unknown)

1.2 Climate and Land Use Changes

According to the Intergovernmental Panel on Climate Change (IPCC), anthropogenic carbon-based emissions are increasing concentration of so-called greenhouse gases, such as carbon dioxide and methane in the atmosphere. These emissions come from a variety of sources but the primary human contribution to the atmospheric carbon balance is through combustion of fuels.

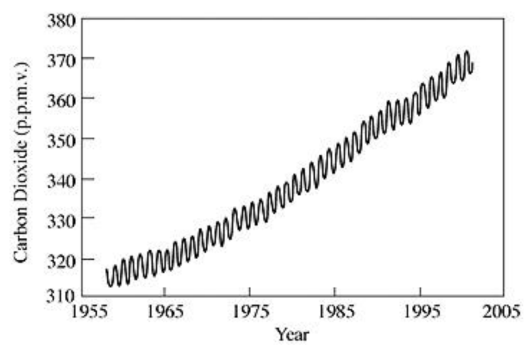

Figure 1.1 CO_2 Concentrations Measured at Mauna Loa Observatory, Hawaii

There have been many estimates of the potential contribution of solar cookers to reducing global climate change. One optimistic estimate cites a potential reduction of fuelwood use by 36% due to solar cookers, which corresponds to approximately 246 million metric tons of wood each year (Tucker, 1999). Assuming an average of 6.28 MJ/kg for wood and 90 grams equivalent CO_2 emissions per MJ energy provided by fuelwood (calculated from values given by Grupp et al. (2002)), this corresponds to equivalent CO_2 emissions of 565 grams per kilogram of wood burned. Therefore, the optimistic estimate would provide for a net greenhouse gas offset of nearly 140 million metric tons per year.

Unfortunately, there is little available data on the number of solar cookers currently in operation on a global scale. Solar Cookers International is working on addressing this problem but at this time that information is still unavailable. Preliminary estimates place the number of solar cookers in regular use, worldwide, as approximately 1.5 million. Though many more cookers than this have been produced and sold, many people only use their cookers infrequently. Assuming that there are 1.5 million operating solar cookers, globally, and that each one cooks an average of 1 meal per day for 3 people, this results in an emissions reduction of approximately 690 million kilograms (equivalent) of CO_2 per year(Grupp, 2002).

Global climate change is a pressing concern, both environmentally and socially, with the potential to affect billions of lives and the entire global biosphere. According to the IPCC, there is a significant contribution to climate change brought about through the combustion of fuels in a manner that is not carbon neutral. Through offsetting some of this fuel usage through the use of solar cookers or other technologies, a corresponding decrease in emissions can be realized, as part of a strategy to minimize carbon emissions. Though further study is needed to understand the relative costs of carbon mitigation strategies, it is likely that solar cooking presents a viable option for emissions reduction on a global scale.

1.3 Difficulties in Assessing Solar Cookers Under Current Conditions

Inventors, engineers, and backyard enthusiasts have created literally hundreds of different types of solar cookers. This wide variety of designs complicates efforts to standardize and evaluate solar cooking devices. Work by Funk and Larson (2000) in the United States has led to the creation of American Society of Agricultural Engineering(ASAE) Standard S580, which sets forth a rigorous procedure for conducting thermal testing of the solar cooker and provides a framework for establishing a 'Cooking Power' normalized to a standardized insolation[1].

Other standards besides that used by the ASAE exist but are difficult to obtain. The standard developed by the European Committee on Solar Cooking Research in 1992, for example, is very comprehensive and includes many qualitative factors such as ease of use and safety (ECSCR, 1992). In India, the Bureau of Indian Standards uses a testing method based on work by Mullick et al. (1987). The Indian standard uses derived figures of merit based on thermal performance to evaluate solar cookers.

These varied standards, each with its own strengths and weaknesses, are problematic to the potential user or supplier of solar cookers. Non governmental aid organizations often find themselves wasting precious time and resources trying to choose the best solar cooker for a given application. Often, solar cooking is neglected entirely because of the difficulty in choosing a design suited to the situation.

[1] Insolation: incident solar radiation, given as an energy flux per unit area per unit time (i.e. W/m^2)

1.4 Goals of the Present Work

The present work focuses on combining the strengths and addressing the weaknesses of the current testing standards for solar cookers. This will be accomplished through the development of an evaluationary framework that combines rigorous and repeatable thermal characterization with more subjective assessments of cooker ergonomics and safety factors. Much of the discussion in the present work will focus on the solar box cooker, though other types are briefly described. The testing standard developed includes these other types but the box cooker is given the widest consideration due to its widespread global usage, particularly in the developing world.

2.0 Theoretical Background on Solar Cooking

From a conceptual perspective, solar cooking is relatively simple. However, it is important to have a basic understanding of the underlying principles used by solar cooking devices if an evaluating framework is to be developed for testing these devices.

2.1 Solar Box Cookers (Solar Ovens)

The Solar Box Cooker (SBC) or Solar Oven consists, largely, of some type of heat trapping enclosure. Quite often, this takes the form of a box made of insulating material with one face of the box fitted with a transparent medium, such as glass or plastic. This allows the box to take advantage of the greenhouse effect and incident solar radiation cooks the food within the box.

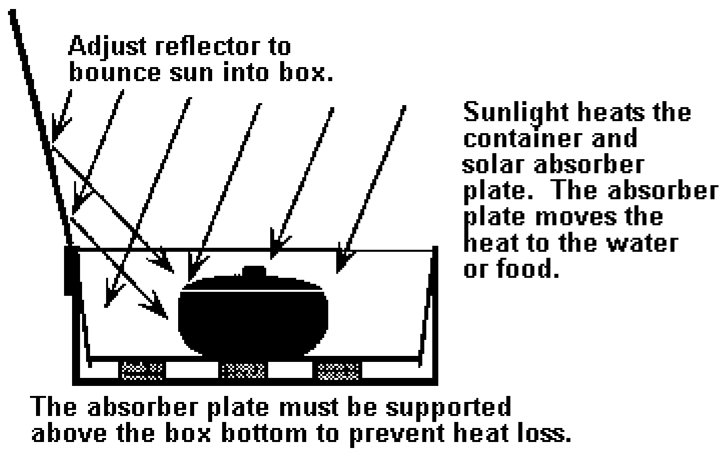

Figure 2.1 is a schematic of the operating simple solar box cooker. Image courtesy of Solar Cooking Archives, www.solarcooking.org/spasteur.htm

The ability of a solar cooker to collect sunlight is directly related to the projected area of the collector perpendicular to the incident radiation. For example, a large box with a glass lid will function as a solar box cooker but the losses due to heat loss over a larger surface area will, at least partially, offset the additional gain through having a larger collector surface. Instead, what is typically done is to create an insulated box with a glazed surface cover and use reflectors to increase the apparent collector area. These reflectors can be made from a variety of materials and their primary purpose is to reflect sunlight through the glazing material and into the cooking space inside of the box. In most cases, these reflectors are planar in geometry, with parabolic and other geometries reserved for the more complicated class of solar cookers that utilize high concentration ratios[2], as discussed later. While a high concentration ratio allows a potentially higher temperature and flux, high concentration ratio devices generate nearly point source foci, which require regular and frequent tracking to follow the sun. Without this tracking, the focus will quickly deform, resulting in an uneven flux and potentially damaging heat gain. One of the virtues of the solar box cooker is its high acceptance angle[3] and correspondingly high tolerance for tracking error. A Solar Box Cooker will cook meals unattended for long periods of time because the sun is able to remain within the view of the cooker. With some other collector configurations, the sun quickly moves off-axis, causing focus shift that can be highly undesirable or dangerous.

In the case of the simple box with no reflectors, the energy entering the aperture can be given simply as:

$$Q_{cooker}=A_{aperture}\tau_{glazing}I_{solar} \qquad \text{(Equation 2.1)}$$

[2] Geometric concentration ratio is defined as $A_{aperture}/A_{receiver}$, where $A_{aperture}$ refers to the total collector area and $A_{receiver}$ indicates the area of the receiver/absorber surface.
[3] Angle through which the sun's image remains on the absorber

Where $A_{aperture}$ represents the area of the 'window' of glazing material that is facing the sun (assumed perpendicular in this equation), $\tau_{glazing}$ is the transmissivity of the glazing material, and I_{solar} is the value of the global solar radiation perpendicular to the collector.

This deceptively simple equation assumes that the collector is normal to the incident radiation. In reality, the apparent area of the collector will change with the angle of the sun, as the collector will appear smaller when the angle between the normal of the collector and sun is large. This variation is given by:

$A_{apparent}=A_{perpindicular}\cos(\theta)\cos(\phi)$ (Equation 2.2)

Where θ is the solar azimuth[4] and ϕ represents the difference between the solar elevation[5] angle and the collector tilt angle[6]. Knowledge of the minimum and maximum values for the azimuth and elevation on a given day allow the integration of the above equation to obtain a daily energy input into the solar cooker.

The simple box can then be expanded by adding one or more reflectors. There is some tradeoff in the design of these panels. In selecting a tilt angle, it should be realized that if the angle between the normal of the glazed surface and the reflectors is small, the reflectors will intercept a relatively small area of sunlight per unit area of reflector material. Conversely, if the angle is large, it will

[4] Azimuth angle is defined as the coplanar angle between a line pointing due south and a line pointing towards the sun, as seen from a stationary observer
[5] Solar elevation angle is defined as the angle of the sun's position relative to a plane tangent to the earth upon which the observer is standing
[6] Angle between the collector normal and a plane tangent to the earth upon which the collector is sitting.

become difficult for reflected light to enter and penetrate the glazing surface due to the shallow reflection angle. A further potential complication is the decision whether to orient the reflectors to take advantage of azimuth or elevation variations. In the case of azimuth variations, a reflector designed to enhance morning performance could act to hamper later afternoon/evening collection, and conversely for improving evening collection.

There are further complications to the case of the simple box that are worth examining. For real materials, τ will change with incident angle and wavelength. In addition, a full assessment would require inclusion of sky diffuse radiation and ground reflected radiation. These are neglected in the current discussion.

Energy gain through the glazing is balanced by heat loss through the exterior of the box. This conduction heat loss is generally greatest through the transparent medium, which typically has a much larger thermal conductivity than the body material of the box itself.

Heat transfer occurs through the standard three mechanisms; radiation, convection, and conduction. For most applications, radiation can be neglected due to the low temperatures occurring at the exterior of the box. Convection can become quite significant, particularly for cookers that do not utilize a well insulated box to hold the food. As wind velocity increases, the heat transfer coefficient increases, thus increasing the heat loss. Cold ambient temperatures and wind work together to reduce the effectiveness of any solar cooker. Combined with cloudy conditions, these effects can render a solar cooker ineffective.

Finally, the steady state temperature inside the box can be calculated by setting the heat loss equal to the energy gain. Terms can be added to this equation to take into consideration any objects within the cooker, such as pots and food. Placing thermal mass (such as pots, food, water, etc.) within the cooker will reduce the temperature of the air within the cooker but it will also diminish the temperature swing caused by opening and closing the box due to increased thermal inertia.

The SBC can also function as a heat-retention based cooker. Aside from the reflectors, the SBC is essentially a well-insulated box. It has been shown that nearly all of the energy required to cook food is spent in the sensible heating stage, as the food reaches cooking temperature (Mullick, 1987). Once this has occurred, the energy input required to continue cooking is very small, its primary purpose to offset heat loss and maintain the food at cooking temperature. Some regions of the world have had success using hay boxes (i.e. simply built, well insulated boxes) to continue to cook food without the need to continue burning fuel. Food is heated initially over a conventional fire and then placed into the hay box. The lid is closed and the food continues to cook inside the box for hours afterward. Significant fuel savings can be realized, as well as benefits to free time and indoor air quality.

2.2 Panel Cookers

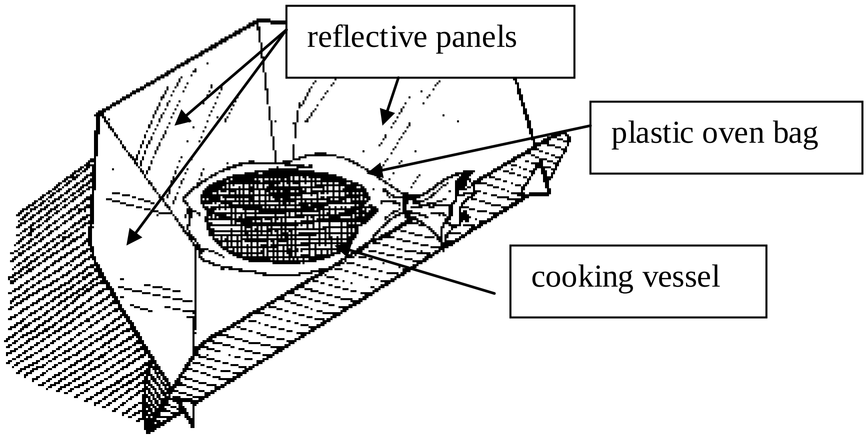

Figure 2.2 displays the layout of the Solar CookIt from Solar Cookers International. Image courtesy of the Solar Cooking Archives, www.solarcooking.org

The panel cooker is quite similar in operation to the SBC. The same principles are employed but instead of an insulated box, panel cookers typically rely on a large (often multi-faceted) reflective panel, as seen in Figure 2.2. At the focus of the reflector rests the cooking pot contained within a transparent medium, such as an oven bag or a glass bowl (FSEC, 2002). Energy from the sunlight is reflected into the bowl or oven bag, heating up a dark painted pot and whatever may be inside of it. The pot in this case is generally less insulated from the environment than the pot in the case of the SBC. The panel cooker relies much more heavily upon reflected sunlight and less so on heat retention as compared to the SBC. This can make the panel cooker more portable and cheaper to construct but the panel cooker will suffer from generally somewhat poorer performance, particularly on days of marginal insolation or intermittent cloudy conditions.

2.3 Concentrating Solar Cookers

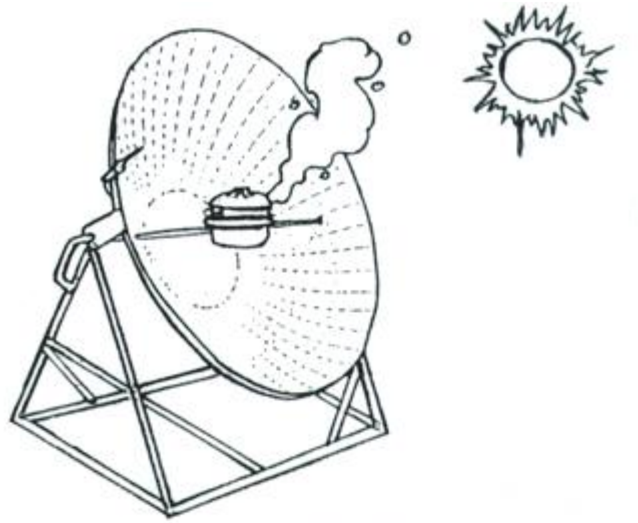

Figure 2.3 shows a simple parabolic solar cooker. The reflector focuses the sunlight on the bottom of the absorber plate, heating the pot in a fashion similar to a traditional electric or gas powered stove. Image courtesy of the Nepal Center for Rural Technology, http://www.panasia.org.sg/nepalnet/crt/home.htm.

The third major class of solar cooker utilizes concentrating optics. Using mirrors and/or lenses, these cookers can achieve extremely high temperatures. The concentrating cooker is the only class of solar cooker that is truly suitable for frying, as the temperature at the focus can rival that of conventional electric, gas, or wood fired stoves. Similar to the panel cooker, the concentrator suffers from a strong reliance on direct beam insolation. Cloudy conditions and wind combine to make concentrating cookers highly difficult to use. In field studies, the concentrating cooker is not generally chosen due to its need to closely follow the sun (characterized by a low acceptance angle), its relatively high cost, and safety issues as focused sunlight can cause burns or eye damage. Nevertheless, in some applications, solar concentrators can make ideal cookers. So long as direct insolation is readily available and the user is experienced and careful, the concentrator represents a highly useful and powerful cooking tool.

2.4 Other Types of Solar Cookers

There are numerous designs for solar cookers that do not fall neatly into the three categories above. It would be difficult to describe each possible variation but it is important that any evaluation of performance have the versatility to include a wide range of styles and designs.

3.0 Existing Standards: Overview and Analysis

Currently, there are three major testing standards for solar cookers employed throughout the world. These standards differ widely in their scope, complexity, and deliverables. Before proposing a standard to bridge the gap between these three existing standards, it is necessary to examine and understand the standards, as they already exist.

3.1 American Society of Agricultural Engineers Standard ASAE S580

This standard was originally developed by Dr. Paul Funk as an international testing standard for solar cookers. The need for such a standard was recognized and addressed at the Third World Conference on Solar Cooking, in January of 1997 (Funk, 2000). The goal of this standard was to produce a simple, yet meaningful and objective measure of cooker performance that was not so complicated as to make testing in less developed areas prohibitive.

ASAE S580 monitors the average temperature inside a pot of water while the cooker is operated under a set of guidelines given in the standard for tracking procedure, thermal loading, etc. Temperature measurements are made of the water and averaged over 10 minute intervals. Ambient temperature and normal irradiance (solar energy flux per area) are also measured and recorded, at least as often as load temperature. Under conditions of high wind, low insolation, or low ambient temperature, tests are not conducted. The primary figure of merit used by ASAE S580 is the Cooking Power, P. This is calculated through the following procedure.

$$P = \frac{T_2 - T_1}{600} m c_p \qquad \text{(Equation 3.1)}$$

Where:

P = cooking power (W)

T_2 = final water temperature

T_1 = initial water temperature

m = mass of water (kg)

c_p = heat capacity (4168 kJ/kgK)

Equation 3.1 is divided by 600 to account for the number of seconds in each 10-minute interval.

P is normalized to a figure of 700 W/m^2 through the following equation.

$$P_s = P\left(\frac{700}{I}\right) \text{ (Equation 3.2)}$$

Where:

I = interval average insolation (W/m^2)

P = cooking power (W)

P_s = standardized cooking power (P_s)

P_s is plotted against ΔT and a regression linear regression performed.

For standard reporting procedures, a Temperature difference of 50°C is used (i.e. T_{water}-$T_{ambient}$ = 50°C) and the corresponding P_s is reported as the 'Cooking Power' (ASAE, 2003).

While ASAE S580 accomplishes its goals of providing a simple test to establish an understandable and universal figure of merit, the test is lacking in several areas.

Though it was never mentioned as a goal of this testing standard, it should be mentioned that ASAE S580 does not address issues other than strictly thermal performance of the cooker. The single figure of merit is practically valueless for assessing *why* a cooker achieved a certain performance, as it leaves out any direct measurement of heat losses. Therefore, any use of the ASAE standard to analyze the performance of a cooker, rather than simply compare its performance to another cooker would be very difficult.

From a qualitative perspective, ASAE S580 does not address ease of use, safety, or financial issues associated with the cookers under test. Once again, this was never implied as a goal of the standard but it should be realized that this information could be equally important to any party interested in solar cooker evaluation. No matter how exemplary a cooker's thermal performance, if it costs thousands of dollars and is impossible for the average person to operate, the cooker's true usefulness is highly questionable.

3.2 Basis for the Bureau of Indian Standards Testing Method

The second testing standard considered is based on *Thermal Test Procedures for Box-Type Solar Cookers*, by Mullick et al(1987). This standard, presented in a more technical framework than ASAE S580, provides two figures of merit, calculated so as to be as independent of environmental conditions (such as wind speed, insolation, etc.) as possible. The two figures of merit are given by the following equations.

$$F_1 = \frac{T_p - T_a}{H_s} \quad \text{(Equation 3.3)}$$

and

$$F_2 = \frac{F_1 (MC)_w}{At} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H} \right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - Ta}{H} \right)} \right] \qquad \text{(Equation 3.4)}$$

Where:

T_p = temperature of the absorber plate (stagnation)

T_a = ambient air temperature

H_s = insolation on a horizontal surface (taken at time of stagnation)

M = mass of water

C = heat capacity of water

A = aperture area

t = time

T_{w1} = water temperature at state 1 (initial)

T_{w2} = water temperature at state 2 (final)

H = horizontal insolation (average)

By setting a reference temperature and solving Eq. 3.4 for t, a characteristic curve can be developed that describes, for a given set of conditions, how long the cooker will take to reach the reference temperature.

Unfortunately Mullick's standard, like ASAE S580, does not include the numerous qualitative factors that can be equally important in evaluating a solar cooker's performance and feasibility.

3.3 European Committee on Solar Cooking Research Testing Standard

The standard proposed by the European Committee on Solar Cooking Research (ECSCR) explores a wider scope than the previous two standards discussed previously. Much of the test is devoted to observation of safety factors, ease of cooking pot access, estimated durability and other somewhat subjective but useful values. The ECSCR standard also includes an exhaustive thermal testing regime. The evaluation process is driven by several detailed data sheets, which are filled out by the tester. Additional data provided by the manufacturer that is also included. Data is collected under the following conditions for the 'Basic Test':

- Water at 40°C is placed in a pre-heated cooker and temperature is recorded for 2 hours around solar noon (i.e. 11:00-13:00)
- The cooker is fixed towards the sun and left. The time taken for the water inside to cool to 80°C is recorded
- Oil, at 40°C, is heated from 11:00-13:00 and the maximum temperature is recorded

- Hot oil from the previous test is left to cool in the cooker out of the sun. The time taken for the oil to cool to 100°C is recorded.
- Non-preheated cooker repeats the test conducted in 1.
- The pot lid(s) is removed and the time recorded for the water from the previous test to cool to 80°C with occasional stirring
- Water at 40°C is heated with the sun at a low angle. Temperature is recorded as a function of time. This measure is intended to test cooker performance in morning and evening conditions.

There are numerous other tests listed that can be performed but this is considered the 'Basic Test'. The general conditions for conducting any of the above tests using this standard are given as:

- Ambient temperature: 25°C-35°C
- Wind velocity < 4 m/s (at the cooker)
- Global irradiance (horizontal) >800 W/m^2
- Diffuse fraction < 20%

One of the benefits of this procedure is that there is no need to measure normal incidence, which generally requires a tracking pyranometer. This eliminates some additional costs, making the test cheaper and easier to run. In addition, the numerous qualitative observations are quite valuable in determining the effectiveness of a particular cooker, as was discussed previously.

Unfortunately, the ECSCR standard does fall short on several key points.

Firstly, the entire thermal testing standard relies on measurements of time taken for certain conditions to occur (i.e. 'time to reach 80°C'). While this may seem useful at first glance for the average user and is certainly an acceptable measurement for comparison of any cookers that are tested simultaneously; rigorous comparison of cookers tested using this method but not tested at the same time and under the same conditions is highly prone to errors and inaccuracies. The ECSCR standard includes no means of normalization. For example, for the same ambient temperature on two different test days, the horizontal insolation could differ significantly (possibly 25% or more). This would drastically change the results obtained and clearly cookers from the two tests could not be compared to one another without some sort of normalization strategy that is not presented in the ECSCR standard.

Secondly, the test procedure indicates that pots should be filled to 'half of nominal pot volume'. A manufacturer need only include an undersized pot to very seriously alter test results. Inappropriately sized pots filled to half nominal pot volume do not allow for a rigorously established testing standard.

Finally, the complete testing procedure proposed by ECSCR is quite comprehensive and not well suited to multiple testings. The time taken for the basic test alone is 3 clear days (meeting the above given criteria). While this may be ideal for testing a large number of cookers at once, such as was done in Almeria (ECSCR, 1993), an ideal testing standard would allow a certified testing agency to accurately test only a single cooker at a time and simultaneously obtain meaningful, repeatable, and useful results.

4.0 The Development of a New Testing Standard

This section will describe the new standard developed as the focus of this work, including detailed description of the figures of merit proposed. An abbreviated version of the proposed standard, for copying, distribution, and use is provided in Appendix B.

4.1 Issues Addressed by New Standard

The purpose of this new standard is to allow policy makers, non-governmental organizations, professionals, scientists, and other interested individuals and groups to easily compare any two (or more) solar cookers. Such ease in comparison would facilitate improvements to existing designs, attract funding awards for solar cooking projects, lend credibility to the science and industry behind solar cooking, and engender high standards of quality in manufacturing of solar cookers.

The ideal testing standard to meet the above stated goals would have the following characteristics

- Reproducibility
- Understandability
- Efficiency
- Objectivity

and be based upon the following questions, as posed by potential users of solar cookers:

- How long will it take to cook meals?
- Is the solar cooker a good value?
- How hot will the solar cooker get?
- Is the cooker easy to use and convenient?
- Is it safe to use?

Solar cookers are employed by a wide range of people. If these people do not have the knowledge necessary to choose the best solar cooker for their needs, the result could lead to dissatisfaction with solar cookers and a negative response to future solar cooking projects. If solar cooking is to become widespread, it is imperative that solar cooking technologies continue to be standardized and rigorously researched.

4.2 Testing Conditions

There are a number of conditions that must be satisfied in order to validate and standardize data produced as a result of the new testing framework. This subsection focuses on those necessary conditions that must exist prior to and during testing.

4.2.1 Environmental Factors

Barring the use of an indoor solar testing laboratory, the testing of solar cookers must rely, to some degree, upon the weather and climate of the testing site. In order for results to be consistent, these factors must be monitored and accounted for when calculating figures of merit from the collected data.

Wind: Wind, by affecting the convective heat transfer coefficient at the outside of the cooker, can produce drastic changes in cooker performance. With this in mind, should the wind exceed 2.5 m/s for more than 10 minutes during any given test, that data shall be discarded (ASAE, 2003).

Ambient Temperature: Ambient Temperature shall be between 20°C-35°C, measured at the test site.

Insolation: While the ASAE standard does suggest that insolation values be recorded for direct beam radiation, for the current work this is felt to add an unnecessary level of complexity to the testing apparatus. Instead, a measurement of purely horizontal total irradiance is taken. If this value should fall below 500W/m^2 or exceed 1100 W/m^2 during any test cycle, data from that test should be discarded. Values outside of this range either preclude reasonable performance or falsely represent the performance of the device under test. Most measurements in this standard are corrected to a standard horizontal insolation of 850 W/m^2 through the methods described below. This value is based on favorable but realistic expected insolation values.

Precipitation: The presence of any precipitation during the test, even if the above stated conditions are still met, will result in discarding the data for that test.

4.2.2 Controlled Factors

Aside from environmental factors, controlled factors represent the portions of the test that are controlled by the tester. These factors can have a significant impact on the obtained results and are discussed below.

Cooking Vessels: If cooking vessels are not provided with the cooker, inexpensive aluminum cooking pots, painted black on the exterior, are to be used.

Tracking: All cookers are azimuthally tracked every 15 minutes, except as noted in the specific Figure of Merit tests given below. Elevation tracking will occur as per the manufacturer's recommendations given in the literature obtained with the cooker. If no elevation tracking is specified, then none is performed and the cooker is tracked only in the azimuthal direction. If any automatic tracking devices are included, these may be set to operate as normal and are considered part of the cooker. Should the manufacturer specify a tracking frequency other than once every 15 minutes, that frequency should be used. The tracking frequency should be reported in the results, in any case.

Time: Testing shall begin no earlier than 10:00AM solar time and shall continue not past 5:00PM solar time.

Thermal Loading: The cooker test loading shall be done with distilled water in an amount equal to 5000 grams of water per square meter of aperture area of the cooker, at +/- 5°C from ambient. If the cooking vessels provided or being used do not possess sufficient volume to contain this amount of water, note the mass of water used and report it in the results.

Data Collection and Recording: Electronic means of data collection should be employed, such as a data logger. Data should be obtained from each instrument a minimum of once every 10 seconds and averaged over an interval specified in the appropriate figure of merit below.

4.2.3 Measurement Standards

The following standards represent levels of minimum accuracy required in each measurement recorded. These should be considered as guidelines and any measurement error outside the given ranges reported and emphasized in the results.

Wind: Wind speed shall be measured at the testing site by an anemometer with resolution of at least 0.5 m/s.

Temperatures: All temperature measurements shall be made with thermocouples or temperature probes of a type appropriate to the expected temperature range of the cooker(s) being tested. The precision of measurements will be equal to or better than 1°C. Measurement of thermal load temperatures must be carefully controlled. Thermocouple leads must be inserted into the cooking vessel through holes specially drilled in either the lid or the side of the vessel. The probes must be suspended such that they are approximately in the center of the cooking vessel, one approximately 5 cm from the bottom and the second approximately 5 cm from the top. This configuration is intended to identify potential thermal stratification within the pot. Furthermore, any entrance points must be sealed with silicone caulk to minimize air leakage and heat loss. The thermocouple wires will also present a heat loss path and should be insulated as much as possible. The two temperature values will be averaged together to obtain a final temperature of the pot contents.

Insolation: Insolation values shall be measured by a pyranometer, calibrated photocell, or other light-sensing device, calibrated to the solar spectrum. The accuracy of this measurement will be no less than 10 W/m^2.

Aperture Area: Aperture area shall be defined as the projected intercept area of the cooker and all auxiliary reflectors in the plane perpendicular to the average solar elevation angle for the date and location at which tests are conducted.

Time: All time figures used shall be given in solar time, +/- 1 minute. See Appendix A.

Mass: Mass measurements shall be taken with a mass balance to a precision of not less than 1 gram.

4.3 Figures of Merit

Figures of merit are used to provide simple to reference numbers that are assumed to be determined for all cookers in a consistent manner.

4.3.1 Thermal Figures of Merit

From the measurements taken, the data will be reduced to four thermal figures of merit, or standards of performance. These figures will allow easy comparison of different types of solar cookers. In addition to these primary figures of merit, there will be several other factors such as safety, ease of use, and, if available, cost as points of comparison. Due to inaccuracies in temperature measurements near the boiling point of water, all tests involving water will be conducted up to a maximum of 95°C. Should this temperature be reached during any test, the test should be considered concluded and any data for temperatures above 95°C will be disregarded.

Standard Cooking Power: This figure is taken based on the temperature change of the test load under known insolation conditions. The values are corrected to a standard horizontal insolation of 850 W/m^2. The process for calculating this figure is nearly identical to that developed by Funk et al. in ASAE S580, and is given below.

The temperature change of the water shall be measured over 10-minute intervals, and cooking power shall be computed by:

$$P = \frac{MC(T_2 - T_1)}{600} \qquad \text{(Equation 4.1)}$$

Where,

M = Mass of water in cooking vessel

C = Specific heat of water

T_2 = Water temperature at end of interval

T_1 = Water temperature at beginning of interval

Equation 4.1 is divided by 600 because there are 600 seconds in each 10-minute interval.

This cooking power is then normalized to 850 W/m^2 (Funk uses 700 W/m^2) through Eq. 4.2.

$$P_n = P\left(\frac{850W/m^2}{I_{measured}}\right) \quad \text{(Equation 4.2)}$$

Where,

$I_{measured}$ = Horizontal insolation averaged over the 10-minute interval

Finally, these equations must be reduced to a single measure of performance. This is done by plotting P_n against ΔT and performing a linear regression, where ΔT refers to T_{water}-$T_{ambient}$ (recorded for each interval). The *Standard Cooking Power* is taken from this regression for a ΔT value of 50°C. The R^2 value for this regression fit should be reported and the data must be taken until a fit can be made with a R^2 of at least 0.75. The length of time taken for this test should be 4 hours, beginning in the morning or the length of time taken for the pot contents to reach 95°C, whichever occurs first. If R^2 results are below the required 0.75, testing can be continued on a second day and these values added to the regression until the required fit can be achieved.

The *Standard Cooking Power* figure of merit is particularly useful to potential users of solar cookers. Not only does this figure provide insight as to the cooker's ability to cook food but it also allows for devices tested under the proposed standard to be compared to devices tested under ASAE S580, though the latter lacks some of the other figures of merit that are included in the proposed standard.

Standard Stagnation Temperature: The stagnation temperature gives an understandable figure for the maximum possible temperature achievable by a cooker under a specific set of conditions. Knowledge of stagnation temperatures can lead to constructive decisions regarding materials for cookers and cooking vessels. This test is conducted using a dry, empty cooking vessel with two thermocouple leads fixed such that they measure the air temperature roughly in the center of the cooking pot. The initial air temperature in the cooking vessel should be within 5°C of ambient temperature. The *Standard Stagnation Temperature* is simply given by:

$$SST = \left(\frac{T_s - T_a}{(I_{measured})} \right)(850W / m^2) \qquad \text{(Equation 4.3)}$$

Where,

T_s = Highest air temperature reached

T_a = Ambient air temperature, averaged over testing period

$I_{measured}$ = Horizontal insolation, averaged over testing period

Measurements are conducted until values of T_s have stabilized or 2 hours have elapsed, whichever occurs first. If testing is halted at 2 hours, report highest value obtained.

The *SST* gives the temperature to which the air within an empty pot will rise under a horizontal insolation of 850 W/m^2. This test can occur after either of the two water-based tests, provided the cooker is placed out of the sun and fully opened for 20 minutes to allow for an appropriate cool-down period between tests.

This figure is primarily of interest to the makers of solar cooking devices. By knowing the stagnation temperature of a type of cooker, more educated choices related to construction materials can be made. To the user of solar cooking devices, this figure may be less interesting but it will still provide a comparison value for thermal performance. The relatively low heat storage capacity of air, as compared to water, may make heat loss effects more observable using this figure. For example, a small amount of heat loss will have a small effect upon the temperature of a mass of water but when air is used, this heat loss may become more observable, leading to a lower stagnation temperature.

Standard Sensible Heating Time: Perhaps more important to the average user than power and temperature, is the time taken to perform a cooking function. Therefore, this figure of merit indicates how long it will take the cooker under investigation to heat a known quantity of water to 50°C above ambient temperature under a horizontal insolation of 850 W/m^2. The basic equation describing an energy balance on the thermal mass within the cooking vessel is given by:

$$M_W C_W \Delta T = \eta_0 IAt \qquad \text{(Equation 4.4)}$$

Where,

M_W = Mass of water

C_W = Specific heat of water (approximately 4.186 J/kg°C)

ΔT = Difference in temperature between pot contents and ambient

η_0 = Optical and heat transfer coefficient-this is essentially a proportionality constant that combines several factors relevant to the transfer of energy through the optical materials of the cooker and the pot material itself

A = Aperture area

t = Time

Solving this equation for time gives:

$$t = \frac{M_W C_W \Delta T}{\eta_0 AI} \qquad \text{(Equation 4.5)}$$

At any point in time, each term of equation 4.5 is known, except for the combined optical and heat transfer coefficient. In order to normalize *t* to a standard reference insolation of 850 W/m^2 and a standard ΔT of 50°C, the following procedure is used.

$$t = \frac{C\Delta T}{I} \qquad \text{(Equation 4.6)}$$

$$t_0 = \frac{C\Delta T_0}{I_0} \qquad \text{(Equation 4.7)}$$

Where

ΔT_0 = 50°C

I_0 = 850 W/m^2

C = $M_W C_W / \eta_0 A$

$$C = \frac{tI}{\Delta T} \qquad \text{(Equation 4.8)}$$

Substituting Equation 4.8 into Equation 4.7 yields:

$$t_0 = \left(\frac{I\Delta T_0}{I_0 \Delta T}\right)t \quad \text{(Equation 4.9)}$$

Thus, for any set of measured values; ΔT, t, and I it is possible to calculate the *Standard Sensible Heating Time*. It should be noted, however, that for ΔT values that are very high or approaching boiling, the accuracy of this equation quickly breaks down. It only applies in the sensible heating region and if ΔT includes any phase change or otherwise non-linear temperature transient regions, the equation will produce inaccurate results. It is suggested that values for a ΔT of approximately 50°C be used, to ensure that the phase change region is not approached. Data for this test can be taken concurrently with that for the *Standard Cooking Power*.

This figure is of interest to the potential user, as it is of primary importance to know how long it will take to cook meals.

Unattended Cooking Time: This test is conducted after the measurement of *Standard Cooking Power* and *Standard Sensible Heating Time* and is intended to measure how long the cooker can maintain a high temperature without being actively tracked to follow the sun. The cooker is left stationary and the temperature of the pot contents (water) measured, as with prior tests. This continues until the pot contents have decreased in temperature by 20°C from starting temperatures (i.e. the final temperature at the end of the *Standard Cooking Power* test). Once again this time measurement is normalized to 850 W/m^2.

$$t_{c,s} = t_c\left(\frac{I_0}{I}\right) \quad \text{(Equation 4.11)}$$

Where

$t_{c,s}$ = Cooling time, standardized

t_c = Cooling time, measured

I = Horizontal insolation, averaged over test period

Once again, this figure is most important to the potential user, who is likely interested in the relatively unique aspect of solar cooking that often allows unattended heating of food while the user attends to other activities.

4.3.2 Utility Figures of Merit

In addition to the thermal figures of merit developed, there are several factors related to cooker utility that should be considered when evaluating a cooker's performance. These figures of merit are given below.

Cooking Power per kilogram: Once again using the *Standard Cooking Power*, this figure provides some insight into the material efficiency of the solar cooker. Weight is an important consideration in solar cooker use. Not only does weight affect the portability of the solar cooker but it also affects shipping costs, ease of maintenance and cleaning, and other qualities. A solar cooker with a high cooking power to weight ratio will tend to be easy to transport and use for a comparatively strong ability to cook food. The weight measurement should include all parts of the cooker necessary for use, including pots, reflectors, glazing, etc. Pot contents from previous tests should not be included.

Aperture Area per kilogram: This figure of merit helps to determine the effectiveness of material usage in the solar cooker. While a large aperture area implies a greater intercept of solar radiation, a high value of weight indicates that this collection process could be more materially intensive than necessary.

4.4 Other Measurements

There are many qualitative observations and characteristic measurements that can be made. It was discovered that the ECSCR Standard already provides very adequate assessment of ergonomic and safety considerations. The ECSCR Standard provides several easy-to-use worksheets that are filled out by the tester and the manufacturer and these sheets address a wide range of possible questions. While this method is necessarily subjective, the tester must be relied upon to exercise good judgment and attempt to remain as objective as possible. This is facilitated by the small number of possible choices on the worksheets (i.e. Easy, Acceptable, and Difficult), which make it more likely that subjective results will be consistent. For the present purposes, the form sheets suggested in the ECSCR standard are deemed adequate and thorough. A sample of this type of reporting sheet can be found in Appendix C.

4.5 Adaptation of Existing Test Data

It may be possible to reproduce some or all of the figures of merit from tests conducted using existing testing frameworks. Tests conducted using ASAE S580, for example, must only renormalize values for Adjusted Cooking Power to obtain *Standard Cooking Power*. The same data can also be reduced, if obtained in its raw form, into *Standard Sensible Heating Time*.

Determining *Standard Stagnation Temperature* based on ASAE S580 is more problematic. In addition, the qualitative and ergonomic assessment would be completely lacking.

Adaptation from the ECSCR Standard, however, would be less difficult. The only true difficulty lies in the lack of irradiance data provided in reporting using this procedure. If the measured values could be obtained from the test center and corrected to horizontal values, it should be possible to convert much of the ECSCR results into results for the new framework. This also provides the basis for another reason for using the ECSCR qualitative assessment forms-this data can now be freely exchanged between testing frameworks with no loss of data or continuity.

Adjusting existing data to the current framework could displace the need for fresh testing of solar cookers that have already been fairly well assessed by other testing standards, particularly that used by the ECSCR. This could provide the proposed framework with a 'ready made' database of cooker specifications and test results for comparison.

4.6 Reporting Procedure

Reporting of professional test results must include the following:

1. All figures of merit

    This should include both Utility and Thermal figures of merit. If one or more figures are missing, an explanation should be supplied.

2. Temperature of water and air over time (with regression lines, where appropriate)

   These should be presented in graphical form with well-labeled axes.

3. Regression R^2 values for *Standard Cooking Power*
4. Assessment sheets, filled out as completely as possible
5. Any deviations from the procedures or standards specified in this document should be noted within the report
6. A description of the testing apparatus used to obtain measurements should be reported

   This need not be a detailed description but should include, at a minimum, the types of temperature probes used and the type of pyranometer used.

4.7 Using This Standard

It is important not only to be able to produce accurate and reproducible results but to be able to properly interpret those results. In many cases, one or more of the above-described figures of merit may be unimportant. For example, if the goal of a project is to create a permanent, stationary solar cooking device, then figures relating to weight or mass may not be important. Care must be exercised to match the figures consulted with the application under consideration. This standard provides a relatively high number of comparative figures with the intention that there is at least one figure that addresses any possible application. A brief summary of situations where each figure may be particularly important is given below.

Figure of Merit	**Applicability**
Standard Cooking Power	Less important for devices intended as secondary or supplementary cooking method.
Standard Stagnation Temperature	Useful for determining alternative materials for construction. Also partially dictates type of cooking that can occur (i.e. frying, baking, boiling)
Standard Sensible Heating Time	More important for community scale cooking facilities, where a single cooker may need to be shared among multiple people or families
Unattended Cooking Time	Particularly important for developing countries or other subsistence applications, less useful for hobbyists or experimenters
Cooking Power per Kilogram	Important for overseas shipping and for portable cookers, a low value may be desired in windy areas
Aperture Area per Kilogram	Important for portability and shipping concerns, may not be important for stationary facilities. A low value may be desirable in windy locations.

5.0 Discussion and Conclusions

The standard developed as the focus of this work addresses many of the issues inherent in the existing testing frameworks. The proposed standard is more comprehensive than ASAE S580, more reproducible than the ECSCR standard, and is more widely applicable than the BIS standard. Each of these existing standards has contributed heavily to the present work and their usefulness should not be discounted.

However, an evolution to a single, widely accepted and used, standard is the logical progression of the industry. It is hoped that this work will serve as the foundation for that new standard. By bridging the gaps between currently used testing standards, it is hoped that the proposed framework will provide an acceptable alternative to existing methods. The figures of merit are meaningful and clear, even to the layperson, and the testing itself is rigorous and reproducible.

As with any first step, it is clear that this standard is not perfect. There are several aspects that require further development and shall be the subject of future work. In particular, the current standard lacks the ability to account for the subclass of solar cookers that makes use of thermal storage (often in water or an anti-freeze solutions). These types of cookers can utilize their thermal mass storage to cook even after sun has set for the day, greatly extending the cooking time available. Similarly, solar cookers which make use of backup heating sources (such as electric or propane) have not been considered. Either one of these types of cookers could be evaluated using this framework but the results would only reflect their ability to directly convert and utilize solar energy. Certainly, modifications could be made to include these two, and other, types of devices that are currently unable to be fully evaluated. However, this addition could require additional figures of merit, or at least careful consideration of the effects of energy storage on the current figures. This is beyond the scope of the present work but is to be undertaken in the near future.

In addition, it is desirable to conduct proof of concept testing to determine the viability of the proposed standard. At this juncture, weather conditions and available equipment are not conducive to conducting this evaluation. Experimental testing is planned for the near future.

Each of the six figures of merit specified has been normalized to be as independent as possible of environmental conditions. In addition, each figure addresses a potential concern on the part of the user of the cooking device. The supplementary information provided by the observation worksheet, combined with the figures of merit given in this work, produce a viable and definitive assessment of performance for a wide range of solar cooking devices.

6.0 References

Abou-Ziyan, 1998, *Experimental investigation of tracking parabloid and box solar cookers under Egyptian environment*, Applied Thermal Engineering 18, pp. 1375-1394.

Addison, Keith, Unknown, *Journey to Forever Website*, Retrieved November 11, 2003, from www.journeytoforever.org/sc.html.

Ahmad, 2001, *Users and Disusers of Box Solar Cookers in Urban India-Implications for Solar Cooking Projects*, Solar Energy Vol. 69, Nos. 1-6, pp. 209-215.

Anonymous, 1998, *Manual for Solar Box Cookers*, Technology for Life, Finland.

Cengel and Turner, 2001, *Fundamentals of Thermal Fluid Sciences*, McGraw-Hill, New York.

ASAE, 2003, *ASAE S580: Testing and Reporting of Solar Cooker Performance*

Biermann et al., 1999, *Solar Cooker Acceptance in South Africa: Results of a Comparative Field-Test*, Solar Energy Vol. 66, No. 6, pp. 401-407.

Biswas et al., 2001, *Model for empowering rural poor through renewable energy technologies in Bangladesh*, Environmental Science and Policy 4, pp. 333-344.

Buddhi et al., 2003, *Thermal performance evaluation of a latent heat storage unit for late evening cooking in a solar cooker having three reflectors*, Energy Conversion and Management 44, pp. 809-817.

ECSCR, 1992, *Solar Cooker Testing Procedure: Proposal*

ECSCR, 1993, *Results of the First Comparative Solar Cooker Test in Almeria: Validation of ECSCR Test Procedure*

ECSCR, 1994, *Second International Solar Cooker Test: Summary of Results*

ECSCR, 1994, *Solar Cooker Test Procedure: Version 3*

Fairey et al., 2002, *Solar Oven Development and Testing: Final Report*, Florida Solar Energy Center, FSEC 26-58-876.

Funk, 2000, *Evaluating the International Standard Procedure for Testing Solar Cookers and Reporting Performance*

Funk and Larson, 1998, *Parametric Model of Solar Cooker Performance*, Solar Energy Vol. 62, No. 1, pp. 63-68.

Goswami et al., 2000, *Principles of Solar Engineering: Second Edition*, Taylor & Francis, Philadelphia, PA.

Grupp and Wentzel, 2002, *Greenhouse Gas Emissions y Cooking with Different Fuels and Reduction Potential of Solar Cookers*. Synopsis Internal Draft, Lodeve, France.

Kraushaar and Ristinen, 1993, *Energy and Problems of a Technical Society: Second Edition*, John Wiley and Sons, Inc., New York.

Meinel and Meinel, 1976, *Applied Solar Energy: An Introduction*, Addison-Wesley Publishing Co., Reading Massachusetts.

Mullick et al., 1987, *Thermal Test Procedure for Box-Type Solar Cookers*, Solar Energy Vol. 39, No. 4, pp. 353-360.

Nahar, 2002, *Performance and testing of a hot box storage solar cooker*, Energy Conversion and Management 44, pp. 1323-1331.

Nichols, 1993, *The Tracking Solar Cooker*

Nichols, 1992, *Reflections on a Solar Cooker*

Parikh, 1995, *Gender issues in energy policy*, Energy Policy Vol. 23, No. 9, pp. 745-754.

Ottinger et al., 1991, *Environmental Costs of Electricity*, Oceana Publications, New York.

Schlesinger, 1991, *Biogeochemistry: An Analysis of Global Change*, Academic Press, Inc., San Diego.

Srinivasan et al., 1978, *A Simple Technique of Fabrication of Parabloid Concentrators*, Solar Energy Vol. 22, pp. 463-465.

Tucker, 1999, *Can solar cooking save the forests?*, Ecological Economics 31, pp. 77-89.

U.S. Congress: Office of Technology Assessment, 1992, *Fueling Development: Energy Technologies for Developing Countries*, U.S. Government Printing Office, Washington DC.

Appendix A. Calculating Solar Time

All time values used in this framework are given in solar time. Therefore, it is necessary to understand the conversion between local time and solar time. The following calculation is taken from Goswami et al. (2000).

Beginning with local standard time, the solar time is given by Equation A1.

Solar Time = LST + ET +(l_{st} – l_{local}) * 4 minutes/degree (Equation A1)

Where,

LST = Local Standard Time

ET = Equation of Time (corrects for irregularities in the earth's rotational speed around the sun, given in minutes)

l_{st} = Standard time meridian

l_{local} = Local longitude

ET = 9.87sin(2B)-7.53cos(B)-1.5sin(B) (Equation A2)

Where,

B = (n-81)360/364 degrees (Equation A3)

Where, n is the day number, beginning with January 1st as 1, January 2nd as 2, and so on.

Appendix B. Abbreviated Testing Standard for Use and Distribution

A Testing Framework for the Comparison of Solar Cookers

The goal of this document is to present an international framework for comparing solar cookers that is objective, complete, and simple to implement.

Constrained Testing Conditions

There are a number of environmental considerations that will determine the ability of the tester to obtain valid results. Should these conditions not be met, testing results cannot be considered to be valid and reproducible.

Wind: Wind speed must maintain a ten (10) minute average value of less than 2.5 m/s

Ambient Temperature: The 10 minute average ambient temperature must remain between 20-35°C during the testing.

Insolation: Horizontal irradiance must remain between 500-1100 W/m^2, averaged over a 10-minute interval during the entire testing process.

Precipitation: The presence of precipitation will void the affected test results.

Controlled Testing Factors:

Cooking Vessels: The test will be conducted with the cooking vessel(s) provided with the cooker. If no vessel is provided, inexpensive aluminum pots, painted black on the exterior will be used.

Tracking: The cooker under test will be tracked according to manufacturer instructions. If instructions for tracking are not included, tracking will occur, in the azimuth direction, every 15 minutes. Elevation tracking will not occur unless specified by the manufacturer. Automatic tracking devices, if present should be used in place of manual tracking.

Time: Testing should occur between 10:00 and 17:00, measured in solar time.

Thermal Loading: For appropriate tests, cooking vessels will be filled with distilled water equal to 5000 grams per square meter of aperture area. If the cooking vessel cannot hold this amount, record and report the amount of water used.

Data Collection and Recording: Data will be collected and stored via electronic means, such as a datalogger/computer setup.

Measurement Precision:

Wind: +/-0.5 m/s

Insolation: +/-10 W/m^2

Temperature: +/-1°C

Mass: +/-1 g

Time: +/- 1 minute

Testing Procedure

There are four thermal figures of merit defined by this framework.

1. *Standard Stagnation Temperature*
2. *Standard Cooking Power*

3. *Standard Sensible Heating Time*
4. *Unattended Cooking Time*

For all of these figures, temperatures measured inside the cooking vessel are the prime indicator. These measurements are taken via two temperature probes, inserted into roughly the center of the cooking vessel. Temperatures obtained from these probes are then averaged together. In tests involving water, one probe is placed near the top of the pot and the second near the bottom to test for stratification.

Data should be sampled at least once every 10 seconds and averaged over the appropriate interval for calculation purposes.

Standard Stagnation Temperature is a measure of the maximum air temperature reached inside the cooking vessel under normalized conditions. To conduct this test, the cooker is oriented towards the sun (in "full on mode") with an air filled cooking vessel. Temperature measurements are taken as the air inside the cooking vessel is heated by the incident solar energy. Testing is concluded when temperature stabilizes at a constant value (within 2-3%) or when 2 hours have passed. This value is normalized to a total irradiance of 850 W/m^2 through Equation. 1.

$$SST = \left(\frac{T_s - T_a}{(I_{measured})}\right)(850W/m^2) \quad (1)$$

Where,

T_s = Air temperature inside the pot, averaged over testing interval

T_a = Ambient air temperature, averaged over testing interval

$I_{measured}$ = Horizontal insolation, averaged over testing interval

Standard Cooking Power is a measure of how much power is delivered, under normalized insolation, to the contents of the cooking vessel. The cooking pot is filled with a mass of distilled water equal to 5000 grams/m^2 of aperture area and oriented to face the sun. As the water heats up, its temperature is monitored. Testing is concluded when the water temperature reaches 95°C or when 4 hours have passed, whichever occurs first. The obtained temperature over time curve is reduced to a single measure of performance by dividing the testing period into 10-minute intervals. The average power delivered over this interval is given by Equation. 2.

$$P = \frac{MC(T_2 - T_1)}{600} \quad (2)$$

Where,

M = Mass of water in cooking vessel

C = Specific heat of water

T_2 = Water temperature at end of interval

T_1 = Water temperature at beginning of interval

Equation 2 is then further reduced by normalizing the power obtained to 850 W/m^2 through Equation 3.

$$P_n = P\left(\frac{850W/m^2}{I_{measured}}\right) \quad (3)$$

Where,

$I_{measured}$ = Measured insolation averaged over the 10 minute interval

Finally, this is made a single measure of performance by using a linear regression between P_n and (T_{water}-$T_{ambient}$) and finding the value of P_n at a ΔT of 50°C. The regression must have a R^2 value greater than or equal to 0.75 or additional data needs to be taken by repeating this portion of the test.

Standard Sensible Heating Time is a measure of how long it takes for a known quantity of water to heat up by a known amount. Data from testing of the *Standard Cooking Power* can be used simultaneously for this figure as well. From the same data, the heating time can be determined from Equation 4.

$$t_0 = \left(\frac{I \Delta T_0 t}{I_0 \Delta T} \right) \quad (4)$$

Where,

ΔT_0 = 50°C

I_0 = 850 W/m^2

I = Horizontal irradiance averaged over entire interval, t

t = Length of measured interval

ΔT = Temperature difference over measured interval

Unattended Cooking Time describes how long a cooker can retain cooking temperatures unattended while the user performs other activities. To perform this test, the cooker is oriented towards the sun and left there, while water temperature is monitored. This test should be conducted directly after the test for *Standard Sensible Heating Time/Standard Cooking Power* so that the water is initially at a high temperature. The test is conducted until the temperature of the water decreases by 20°C from its starting temperature. The time taken for this to occur is normalized to a standard total irradiance of 850 W/m^2 with Equation 5.

$$t_{c,s} = t_c\left(\frac{I_0}{I}\right) \quad (5)$$

Cooking Power/kilogram is a measure of material intensity and optical efficiency of the cooker and cooker materials. It is simply the *Standard Cooking Power* divided by the mass of the cooker.

Aperture Area/kilogram is a measure of the material intensity of the cooker, not accounting for optical losses.

Ergonomic and Safety Assessment

See attached worksheets

The tester should fill out these sheets during testing. Input from the manufacturers could also be included.

Reporting

For professional reporting, the following should be included:

1. All figures of merit
2. Temperature of water and air over time (with regression lines, where appropriate)
3. Regression R^2 values for *Standard Cooking Power*
4. Assessment sheets, filled out as completely as possible
5. Any deviations from the procedures or standards specified in this document should be obviously noted within the report
6. A description of the testing apparatus used to obtain measurements should be reported

Questions or Comments regarding this standard should be directed to:

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Appendix C. Sample Reporting Worksheets

Solar Cooker Performance Evaluation Worksheet				Page 1
Manufacturer and Model:				
Test Date and Location:				
Cooker Type:	Box	Concentrator	Panel	Other
Physical Description:				
Features:				
Weight (kg):				
Transport dimensions (cm):				
Cooking dimensions (cm):				
Aperture Area (see definition):				
Number of pots provided:				
Total volume of cooking space:				
Pots removable:		yes	no	
Number of steps to access cooking food:				
Comments:				
Safety Aspects				
Burn Risk:		High	Medium	Low
Abrasion Risk:		High	Medium	Low
Other Risk (specify):		High	Medium	Low
Comments:				
Ergonomics				
Transport:	Easy	Acceptible	Difficult	
Set up:	Easy	Acceptible	Difficult	
Pot Access	Easy	Acceptible	Difficult	
Filling of Pots	Easy	Acceptible	Difficult	
Cleaning of Pots	Easy	Acceptible	Difficult	
Cleaning of cooker	Easy	Acceptible	Difficult	
Tracking	Easy	Acceptible	Difficult	
Dismantling	Easy	Acceptible	Difficult	
Comments:				

Durability				Page 2
(expressed as subjective quality of materials and craftsmanship)				
Absorbing surface(s):		Good	Fair	Poor
Reflecting surface(s):		Good	Fair	Poor
Glazing:		Good	Fair	Poor
Insulation:		Good	Fair	Poor
Other Components:		Good	Fair	Poor
Maintenance				
Operating instructions included:		yes	no	
Repair instructions included:		yes	no	
Replacement of broken parts:		Easy	Acceptible	Difficult
Maintenace scheme specified:		yes	no	
Warranty:		yes	no	
Comments:				
Economic Aspects				
Price of cooker (USD, 2004):				
Contact Information for Manufacturer:				
Countries that produce cooker:				
Performance Criteria				
Standard Cooking Power:			Watts	
Standard Stagnation Temperature:			C	
Standard Sensible Heating Time:			minutes	
Unattended Cooking Time:			minutes	
Cooking Power per kilogram:			Watt/kg	
Aperture Area per kilogram:			m^2/kg	
Location of Test Site:				
Latitude:		Longitude:		
Maximum solar elevation:				
Average wind velocity:				
Average ambient temperature				
*Averages calculated over all tests				