Towards an International Standard for Measuring Solar Cooker Performance

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Abstract

Billions of people still depend on food cooked over an open fire. This ancient practice has many serious health and environmental consequences. It is estimated that annually 3.5 million women and children die from respiratory diseases from exposure to cooking smoke. Currently ISO is developing a standard for protocols that measure the performance of improved cookstoves of all types. This includes solar cookers, which have no emissions, use no fuels, and can reduce fuel costs for low-income people and refugees. In the US there is an existing standard for solar cooker power. Using this standard we conducted several heating tests of solar cookers to establish repeatability of temperature measurements. Initial experiments showed a significant lack of repeatability. Some detective work led to the discovery of uneven heat leakage from the gap in pot lids; a sealed lid improved repeatability. Further experiments indicated that temperatures in two copies of a solar cooker design could be expected to agree within 3-5 degrees C, if care is taken to control sources of variation. This experience will be useful in continuing work aimed at refining a protocol for the ISO standard and for constructing automated systems for solar cooker testing.

Background

ABOUT 2.7 BILLION PEOPLE currently depend on an open fire or an inefficient cookstove to cook food [1]. The ancient practice of using wood or charcoal for cooking has many serious consequences, including deforestation, habitat loss, soil erosion, burns, and the excessive and dangerous labor of gathering and chopping wood, which prevents women (the large majority of cooks) from obtaining education or employment. But the most acute consequence of biomass cooking is the health impact of emissions near the cooking fire. The World Health Organization (WHO) estimates that around 6.5 million premature deaths each year can be attributed to air pollution. In fact, the number of deaths attributed to air pollution each year is much greater than the number from HIV/AIDS, tuberculosis, and road injuries combined. Around 3.5 million of these deaths are caused by respiratory diseases of women and small children exposed every day to cooking smoke [2].

To accelerate the transition to improved cooking methods, a Global Alliance for Clean Cookstoves, hosted by the UN Foundation, was launched in September 2010 by then-Secretary of State Clinton through the Clinton Global Initiative. The Alliance, led by CEO Radha Muthiah, has an ambitious 10-year goal to foster the adoption of clean cookstoves and fuels in 100 million households by 2020. By 2015 the Alliance had gathered over 1300 partner organizations and was on target to exceed its mid-term goals [3].

In 2013 US leaders from the Environmental Protection Agency's Partnership for Clean Indoor Air and the Department of Energy (DOE) met in Washington to recruit a team of interested scientists to support the development of an international standard for "Clean Cookstoves and Clean Cooking Solutions" [4]. The author is currently a member of two of the four working groups creating drafts of the standard, which is now designated as ISO-19867 [5]. The groups are developing protocols for measurement of power, efficiency, emissions, durability, safety, and user acceptance of cookstoves. The work now involves experts from over 25 countries. The scope covers all types of household-scale devices for cooking food and heating water, and all energy sources [6].

Solar cookers (or cookstoves) are of particular interest to the author. They have no emissions, use no fuels, and can have a low total cost of ownership. They are especially suitable in regions where there is ample solar radiation (insolation). Many of these locations, including most refugee camps, are in sub-Saharan Africa, the Middle East, India, and northern China.

Solar thermal cookers use concentrated sunlight to heat food. They do not use photovoltaic technology. They are simple, low-tech devices that come in a wide variety of designs. The three main types of solar cookers that are in common use are:

1) Panel cookers, which use an arrangement of flat or curved reflectors aimed at a black cooking pot, with a transparent cover around the pot to reduce heat loss.
2) Box cookers, which use an insulated box with a window on top and one or more flat reflectors aimed into the box.
3) Parabolic cookers, which use a doubly-curved mirror that focuses concentrated sunlight onto the cooking vessel.

Panel and box cookers are low-power devices that operate like an electric slow cooker (*e.g.* the Crock Pot™), whereas parabolic cookers are high-power devices that are suitable for fast stir-fry cooking at high temperatures. A comprehensive catalog of solar cooker designs has been compiled [7].

Solar cookers can complement – but are not intended to replace – the fuel-based cookstoves, for two simple reasons: clouds and darkness. When sunlight is not adequate, an alternative method must be used for cooking. Hence solar cookers are intended to work in concert with other methods, serving to reduce fuel use and emissions when weather permits. They can also be used with a heat-retaining device (such as a large insulated basket) to keep food hot and continue the cooking process until dinner time [8].

Solar Cooker Performance Measurements

The heating or cooling of any object is governed by Newton's law of cooling. He observed that the rate of temperature change of a body is proportional to the difference in temperatures between the body and its surroundings. We now write this general observation as:

$$\frac{dQ}{dt} = -K\big(M - Q(t)\big)$$

where M is the maximum temperature that can be attained at equilibrium with the heat source, and $Q(t)$ is the actual temperature of the object at any time t. K has units of time^{-1}. The inverse of K is a characteristic time constant which indicates how fast the object's temperature can change. (The time constant is determined by the mass of the object, its thermal conductivity, surface area, and other factors. The solution to this equation shows that the heating or cooling occurs exponentially, e^{-Kt} and is generally determined by experiment.)

In the case of solar cookers the heat source is the Sun and $Q(t)$ is the internal temperature of the cooker. Solar cookers need to be aimed toward the Sun to maintain the maximum illuminated area of sunlight. Depending on the design of the particular cooker, it may be more or less sensitive to changes in the Sun direction. Cookers made with parabolic reflectors are very sensitive to the Sun direction and will need to be turned more or less continuously. Panel or box cookers typically need to be turned much less frequently.

With the Sun at the zenith on a clear day the direct solar irradiance is about 1000 Watts/m^2, but it varies as the Earth turns. An extension of Newton's law can account for variation in the heating power. To first order solar irradiance varies as $\sin\theta$ where θ is the altitude of the Sun. With this extension, Newton's equation becomes:

$$\frac{dQ}{dt} = K\big(M(t) - Q(t)\big)$$

where $M(t) - E\sin\theta(t)/\sin\theta_0$. E is a constant (the equilibrium temperature), and θ_0 is the Sun's altitude at the beginning of the measurements. Given the date and the latitude of the test location, the altitude of the Sun $\theta(t)$ can be obtained conveniently from the online calculator at the US Naval Observatory [9].

Several countries already have developed national standards for measuring the performance (*i.e.* power and efficiency) of solar cookers. In the US the standard is ASABE (American Society of Agricultural and Biological Engineers) S580.1 [10], which was developed by Paul Funk [11]. Tests performed using this standard were reported at the Clean Cooking Forum 2015 in Ghana by Jim Jetter, who operates the cookstove testing laboratory of the US Environmental Protection Agency [12].

Regardless of what protocol is used in the ISO standard for performance measurements, the following steps will need to be taken to set its parameters appropriately and assess its practicality and suitability:

1. Define instrumentation requirements needed to perform the protocol.
2. Conduct several heating tests of solar cooker models to establish repeatability of temperature measurements and to determine causes of variability in data.
3. Conduct multiple tests in accordance with the protocol to determine if it yields repeatable and reproducible measurements of power and efficiency.
4. Determine if any revisions to the proposed protocol are needed to make it more complete, easier to use, and/or more practical in an international standard.

The instrumentation used for preliminary measurements is listed in the Appendix. The instrument package is currently being revised based on new technology developed by Martin Steinson at the National Center for Atmospheric Research in Colorado. The new instruments are created using 3D-printed components and low-cost Raspberry Pi computers. These will lead to a system that is much smaller and lower in cost than previous weather instrumentation [13].

Establishing Repeatability of Solar Cooker Measurements

The remainder of this article addresses the second step in the above list: a preliminary series of experimental measurements of internal temperatures in a solar cooker. As with any measurement that may be affected by many variables, it is important first to make repeated measurements under what are believed to be the same conditions, and to determine whether in fact repeatability was achieved. If not, this indicates that there are one or more important variables that have not been controlled. Continued careful testing may be necessary before these variables are discovered and controlled (either by eliminating them, keeping them the same in all experiments, or finding a way to compensate for their influence).

For the first series of measurements the test item was a panel-type solar cooker called the HotPot (Figure 1). It consists of a foldable aluminum reflector and a 3-part vessel with a glass outer bowl, a black steel inner pot, and a glass lid. The outer bowl serves to keep hot air around the inner pot to reduce heat loss. The capacity is 5 liters. The HotPot was designed by the Florida Solar Energy Center with support from Solar Household Energy, Inc. and who received a World Bank Global Development Marketplace grant to promote its adoption in several rural Mexican communities in 2003 [14]. Twenty thousand of them have been distributed through projects in Mexico [15].

Figure 1. HotPot in use in Sierra Gorda, Mexico

Figure 2 shows an example of three repeated measurements of the internal temperature of a HotPot. Samples at 30 second intervals were logged in tests conducted in Tucson, Arizona, on three days with clear skies in 2012. The measurements started at 10:00 am; nearby pyranometer data from the University of Arizona in Tucson confirmed that the sky was clear on each of these days [16]. One liter of water was heated in the pot, and the reflector's azimuthal angle was turned toward the Sun direction once per hour.

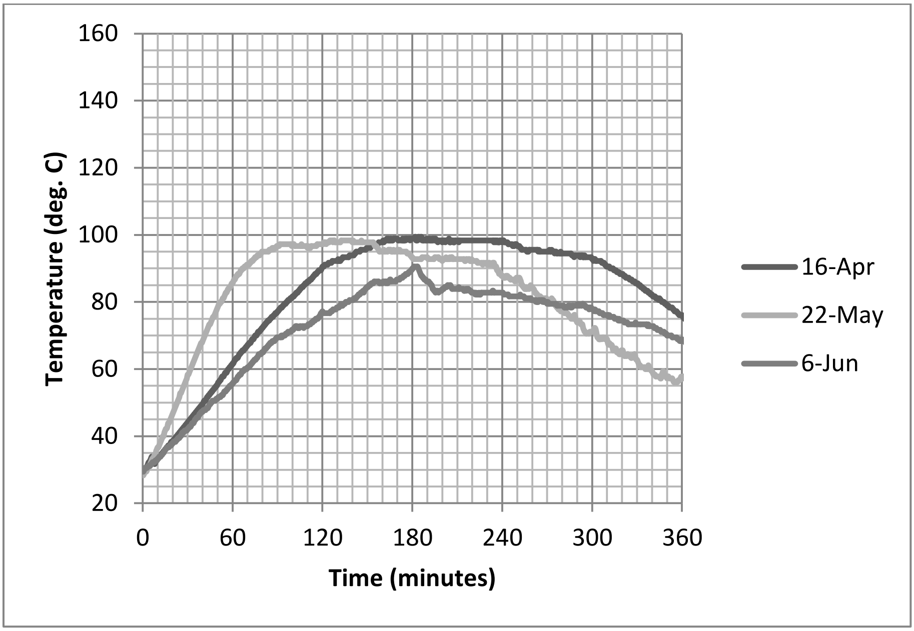

Figure 2. Internal temperatures in the HotPot on three days

Clearly these measurements were not repeatable. The measurements showed a heating rate that varies by more than a factor of two. Something caused these data to be non-repeatable. We noted that the solar irradiance was within 1% on all three days, as recorded by precision instruments. Wind speed was monitored and was low on all three days. There was a slight difference in Sun angles for the three dates, but these are not significant for a panel-type cooker like the HotPot. Positioning of the reflector was the same for all tests.

Lack of repeatable, predictable performance has implications for household use of solar cooking. If a cooker does not achieve sufficiently high temperature during use, it may not adequately cook the food. To reduce this risk, a water purification indicator (WAPI) is widely distributed along with solar cookers. The WAPI consists of a small tube containing a wax that melts at 65 deg. C, which is the temperature above which water is pasteurized [17]. This device is helpful, but as with any cooking appliance, adequate cooking power and repeatable performance are also important to ensuring food safety.

As a starting point in tracking down the source of variation, it is helpful first to ask, “Where is the main source of heat loss?” The most obvious source is the gap between the lid and the pot. Other variations may have to do with the placement of the thermocouple in the pot, or variations in the electronics of the instruments. So a second experiment was conducted to determine repeatability while the pot is cooling. Two copies of the HotPot were placed side by side, indoors, and a liter of hot water was poured into them. Then the temperatures were recorded as the pots cooled. The results are shown in Figure 3.

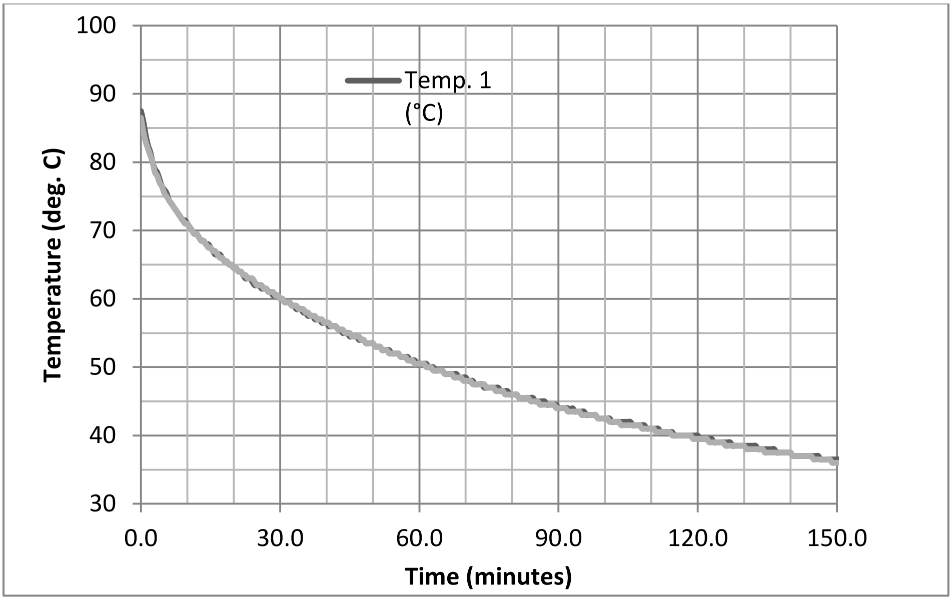

Figure 3. Internal temperatures in two HotPots during cooling

At this scale, the data from the two sensors overlap each other. Close examination showed that after the first few seconds, the two thermometers gave readings that matched within 0.5 deg. C (the resolution of the instruments).

Why is there such a high degree of repeatability in cooling but not in heating? Before answering this question, we conducted another experiment using oil rather than water as the load in the pots. This experiment was conducted in Rockville, Maryland on August 5, 2015 under partly cloudy conditions, so there is some variability due to clouds moving past the Sun. However, two HotPots were measured simultaneously, so these variations can be expected to be the same in both data sets. Figure 4 shows the pot internal temperature measurements.

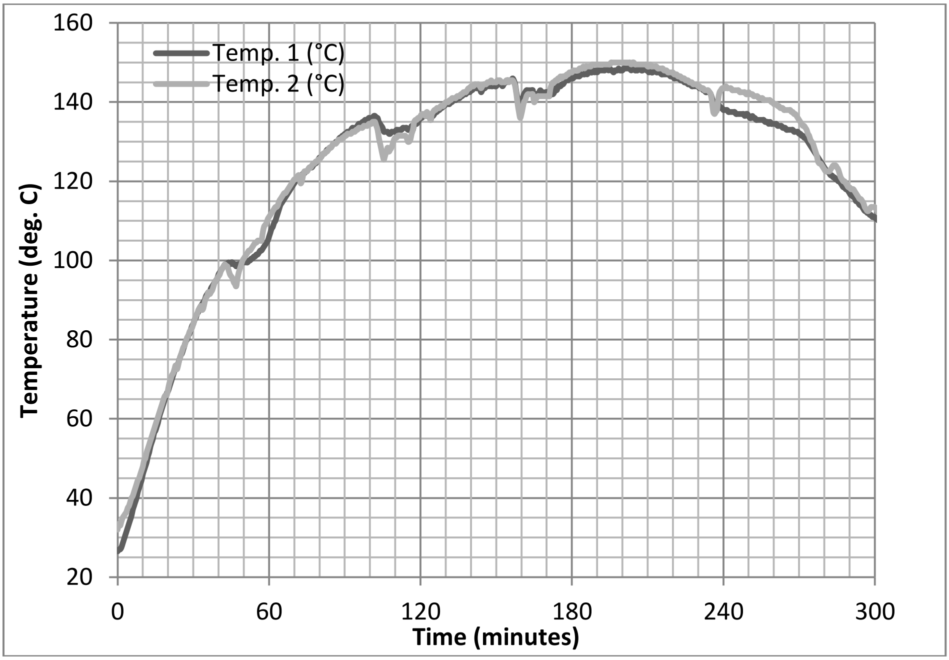

Figure 4. Internal temperatures in two HotPots with 1 liter canola oil load

These data show good agreement between the temperatures in the two copies of the solar cooker with an oil load. (Small spikes in the data occurred as the reflectors were turned about once an hour to track the Sun.) Attempting to account for this agreement, we focused our attention once again on the gaps in the lids of the HotPots. There are slight manufacturing irregularities in the flatness of the lids. In the case of heated water vapor is formed, and the vapor pressure increases rapidly as the boiling point is approached (one liter of water expands to 1700 liters of steam). In the case of oil the boiling point is much higher, so much less pressure is generated (due only to thermal expansion of the air in the pot, about 40%).

To visualize the effect of uneven gaps in the pot lids a small amount of dry ice and water were inserted into a pot placed on a black cloth. A photograph of the leakage of vapor spilling from the lid gap is shown in Figure 5.

Figure 5. Visualization of vapor escaping from lid gap of HotPot

An examination of several figures like this showed that the venting of vapor from the pot varies with lid position, and also the amount of variation depends on the angle at which the lid is placed on the pot. This observation helps to explain why even one pot showed non-repeatable results: the lid was not placed on the pot at the same angle in each experiment.

After further experiments in which the angle of the lid was marked and kept the same the repeatability improved. This episode illustrates the care required to achieve repeatable results, which discloses a tacit but false assumption of symmetry of the test item.

A practical recommendation to manufacturers arising from this series of experiments is that for efficiency and repeatability, it is important to control the lid gaps in pots of low-power cookers. This was confirmed in a subsequent test in which the lids were sealed with aluminum duct tape, with only small gaps open to permit passage of the temperature probe wires. Figure 6 shows this result.

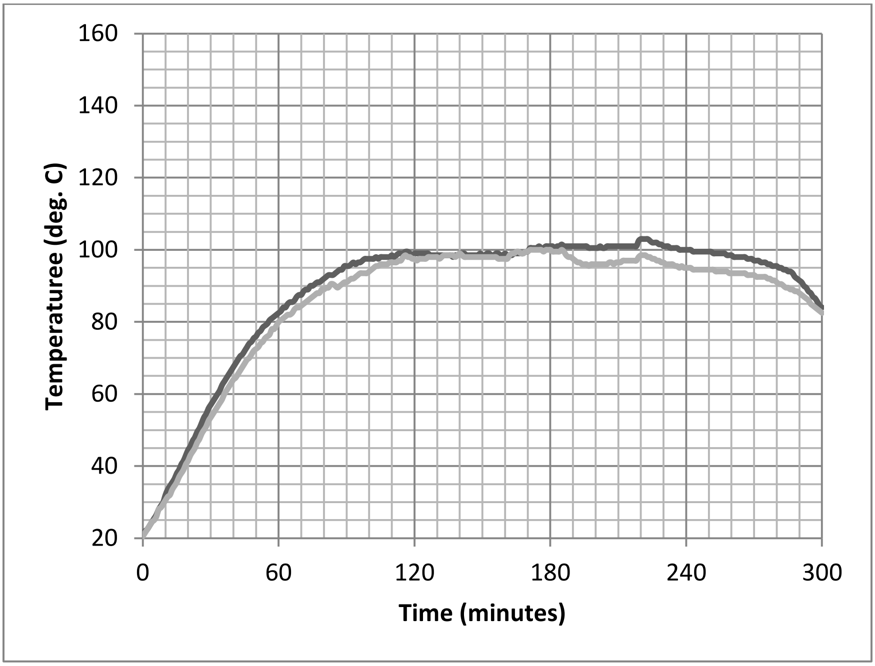

Figure 6. Internal temperatures in two HotPots with lids partly sealed

In this test done in Rockville, MD on a clear day (Sept. 14, 2015) the solar cookers reached boiling in two hours. Each pot had one liter of water as the load. Temperature differences of 3 to 5 deg. C were noted, but the heating curves are otherwise similar. The water sustained a full boil until the Sun angle became low.

Temperature curves like these can be used to determine heating power, which is based on the temperature change times the heat capacity of the load divided by the time interval. The slope of the early part of the heating curve determines the power; as the curve approaches the boiling point, water changes state and the simple cooling law does not apply. (In this example, the heating power is approximately 55 Watts).

Devices like the HotPot are not intended to have a tight seal – which would make them into unsafe pressure cookers – but provide only some back pressure to control the escape of steam (and hence useful energy) from the pot of food. Subsequent tests with different designs of solar cookers have confirmed that repeatability is maintained within 5 degrees C if the cookers have pots with a rubber gasket around the lid.

Statistical Considerations in Cookstove Testing

Like any manufactured product, solar cookers can be expected to have some variation from unit to unit, which sets bounds on the degree of precision achievable in performance measurements. Measuring instruments are also manufactured products that have limits to their accuracy. This entire research effort is very cost-constrained, so the precision and accuracy required of instruments should not exceed that of the expected variability of the products being tested.

One of the main uses of cookstove performance measurements is to compare one design to another. This may be done for R&D or for product evaluations by consumers. For combustion cookstoves, the power, fuel consumption, and emissions measurements are highly variable, and hence many (at least seven) repeated tests are typically conducted and results averaged [18]. Ideally, one would like to do many repetitions with solar cookers also, in order to improve the confidence in statistical comparisons. However, solar cooker tests are time-constrained. Each test requires one clear day to perform. Therefore it would be very unproductive to require averaging the results of many tests.

Required confidence limits and the level of significance for hypothesis tests have not yet been defined for the ISO standard. However, preliminary solar cooker experiments have established that under matched solar input conditions, the measurements of two HotPot solar cookers with a water load can be repeatable to somewhat less than 5 degrees C. Many more tests will be needed to determine the standard deviation for a large population of experiments, and future experiences may lead to improvements in repeatability.

We anticipate that other researchers may wish to develop instruments and procedures to measure solar cooker performance. For such users, we have summarized the lessons learned from our experiments in Table 1. It lists major sources of variation encountered or expected, and means for mitigating the effects of these errors. Guidance regarding pyranometer usage was supplied by experts at the National Renewable Energy Laboratory [19]. ISO standards for calibration of pyranometers are currently defined [20].

Table 1. Main sources of variation in measurements and how to mitigate them

Source of variation	How to mitigate
Clouds and haze	time average over 10 minutes; exclude data with excessive cloudiness
Solar irradiance (input power)	Normalize load volume; normalize all cooker power estimates to the same solar irradiance level
Sun angle, vertical	Specify in the protocol a minimum Sun angle for which data may be collected.
Sun angle, horizontal	Track the Sun at the appropriate rate
Ambient air temperature	Subtract from pot internal temperatures; Specify in the protocol a temperature range within which data may be collected.
Excessive heat loss due to wind	Restrict measurements to low wind speeds; provide a wind shelter around the apparatus
Lid gaps in cooking vessel	Use silicone rubber gasket to reduce uneven gaps; use very small wires for thermocouples across lid gap; insert wires through a hole in lid; use self-contained data logger in vessel
Water vapor emission from cooking vessel increases with internal temperature	Exclude measurements at temperatures near boiling; use cooking oil instead of water as the load
Position of temperature sensor within cooking vessel	Take great care to position sensor with stiff wire to maintain position in liquid
Shade from nearby objects	Ensure that experiments are done in a place that is not shaded at any time during the day or season
Shape of reflector(s)	Repeat measurements and average; use support structure to maintain proper shape
Reflectors or transparent components not clean	Ensure that reflectors are properly cleaned before each experiment
Condensation of water vapor on transparent components	Ensure that transparent components are properly cleaned to minimize condensation
Energy loss due to evaporation of water while boiling	Protocol should define only the heat gained in the cooking vessel as useful energy for cooking
Altitude above sea level	Restrict temperature measurements to 5 deg. C below local boiling point
Heat capacity of load varies with temperature	Minor effect; use available heat capacity data to adjust if necessary
Systematic errors in temperature measurements	Check for offset in temperature compared to a precision absolute reference using a water bath

Next Steps in Applying the ISO Standard

Establishing repeatability does not necessarily establish reproducibility. The latter implies the ability for another experimenter in another location to independently conduct tests and obtain nearly the same results. This will require the use of calibrated instrumentation traceable to reference standards, adjustments for different latitudes, altitudes and other factors. In future tests with revised, portable instrumentation, a series of "round robin" experiments will be conducted to establish reproducibility.

There are over 40 "Regional Testing and Knowledge Centers" around the world that have been established to perform power and emissions tests on combustion cookstoves [21]. One intent of the solar cooker research reported here is to provide a low-cost, portable instrument package to support the measurement of solar cooker power in accordance with a practical protocol included in the future ISO standard for solar cookers. This will enable these Centers to expand their capabilities: to provide a way to conduct reproducible evaluations of solar cookers as well as other types of cookstoves.

Conclusions

Numerous experiments with combustion cookstoves over many years have served to build up a sufficient base of experience to define ISO standard protocols for performance measurements for these devices. The experiments on solar cookers described above represent a small step in the ongoing research leading toward a practical protocol for solar cooker measurements in the ISO standard.

An ISO standard for cookstoves will support significant health and environmental benefits for the world. High quality standards will raise credibility and build confidence in products through standard ratings and certifications. Standards will put pressure on manufacturers to improve performance, safety, and durability. Countries will be able to establish consistent regulations. Program managers will have an easier time identifying suitable products to subsidize or promote, which will reduce investment risks.

There are significant social as well as technical challenges in introducing innovative cookstoves to the world. Solar cookers, in particular, are a disruptive technology. Although they can greatly reduce labor, fuel cost and emissions, they require changes in the cooking methods and daily lifestyle of cooks. Hence their introduction must be supported with ample participation of actual users in each particular region to provide feedback. Managers of solar cooker distribution projects have learned that sustained, user-focused, bottom-up management practices are necessary to encourage users, build local buy-in and maintain support for improved cookstoves that are to be introduced into traditional cultures [22]. Successful adoption of any new cooking method is dependent on the motivation of the cooks, not just products or technology.

Acknowledgements

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Bio

Paul Arveson received a BS in Physics from Virginia Tech in 1966, and an MS in Computer System Management from the University of Maryland University College in 1999. He has worked in underwater acoustics and oceanography as a civilian research physicist for the Navy. His last position was as a Senior Associate at the American Association for the Advancement of Science (AAAS). He is a Fellow of the Washington Academy of Sciences, and currently serves on the board of that organization.

Appendix
Preliminary Instrumentation for Solar Cooker Performance Measurements

1. 4-channel 16-bit analog data logger, UX120-014M, Onset Computer Co.
2. 4 signal cables, 2.5mm x 10 ft., Video Products Inc.
3. 4-channel thermocouple data logger, Onset Computer Co.
4. Type T thermocouple sensors, pack of 5, STC-TT,T,24-72, Omega Engineering Inc.
5. 4 Miniature thermocouple connectors, SMPW-CC-T-M, Omega Engineering Inc.
6. Pyranometer, Institute for Earth Science Research and Education, www.instesre.org
7. Anemometer, Item 1733, Adafruit Co., www.adafruit.com
8. Acropower 15W PV Solar Panel module 12V
9. JVR Solar Panel Charge Controller 12V

Total cost of instruments: $721.40
(This list does not include assorted cables, enclosures, batteries and other items used in the assembly of apparatus.)

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