DEVELOPMENT AND OPTIMIZATION OF A THERMAL-STORAGE SOLAR COOKER

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ABSTRACT The solar cooker is one that stores solar heat in a sealed container of melting salt for six-to-seven hours during a tropical day. When all the salt is melted, or at around 4 PM, whichever occurs first, the cooker is automatically fully insulated thermally and can be used for cooking in the evening, three-to-five hours later. A somewhat crude version of the cooker has shown that the thermal-storage concept is fully feasible, using a solid copper finned hot plate as the interface between the thermal storage and the heating surface. This paper reviews past work and discusses future work to be carried out under funding from the Tata Center for Technology and Design at MIT

BACKGROUND TO THE FUNDAMENTAL PROBLEM

There have been many reports of women in dry tropical areas having to walk ten-to-thirty kilometers per day searching for firewood, exposing themselves thereby to rape and other violence, and producing desert-like conditions as all available wood and dung are scavenged (Bilger, ref. 1)

Why is the topic important - views of the former secretary of state

. . . "Kris Balderston, the State Department's representative for global partnerships.. . . pointed to a bookcase stocked with . . . .advanced cookstoves. "This is a problem that the Secretary [of State Clinton] saw when she was First Lady," Balderston said, explaining how lethal cooking smoke can be. "One half of the world cooks in open fires. Two-million people per year die from it—that's more than malaria and tuberculosis combined, and nearly as much as H.I.V." On a trip to the Congo in 2009, Clinton met a woman in a refugee camp who had been raped in the jungle on the outskirts of the camp while gathering wood for her stove. Telling the story at the State Department, Clinton was angrier than Balderston had ever seen her. "We have got to do something about this," she said.".. . *(Lizza, ref.2).*

Previous work: what is the potential for impact?

The author taught for two years in northern Nigeria and thus appreciated the need for improved cookers, later worked with a VITA team (Volunteers for International Technical Assistance) that produced, from an existing design, an inexpensive robust and effective solar cooker (figure 1) that was introduced to some African countries with Peace Corps collaboration. It used a low-cost fresnel reflector to focus the sun's radiation on the bottom of a conventional saucepan. Many tropical people have, however, a strong antipathy to both cooking and eating in the middle of very hot days, and the cookers were almost unused.

What is known and what is novel about this approach?

From this experience, the author. and his students wanted to make solar energy available in a way that would enable cooking and eating to take place in the evening. We found no evidence of earlier multi-hour thermal storage at full cooking temperature being used for household- and village-level cook-stoves (Akinwale, ref. 3). (A U.S. group has recently (2012) started a similar activity.)

Foregoing work in the present program (Hopping, ref. 4, Mkandiwire, ref. 5 and Matteo, ref. 6) included the choice of lithium nitrate as the optimum thermal-storage material from its energy-storage capability and its ideal melting temperature (see table 1). We confirmed its safety for the intended purposes and chose to use a single large container of the salt into which fins below a cooking hot-plate of solid copper are submerged (figures 2, 3). We also decided to employ a fresnel lens for focusing the sun's energy on to the upper surface of the cooker hot plate (figures 4, 5). An excellent review paper that guided us was by Wyman, Castle and Kreith, ref. 7.

PRELIMINARY DESIGN ESTIMATES

Our estimate for the heat required to prepare an evening meal for a family is 1.5 kW-h, 5.4 MJ. The heat of fusion for lithium nitrate is 367 kJ/kg. Therefore about 15 kg (33 lbm) of lithium nitrate would be needed to be fully molten at the start of cooking The freezing temperature is about 250 C, a little over 480 F, ideal for hot-plate cooking or for baking.

The solar radiant heat in daytime over a wide area of the tropics, between latitudes of +/- 15 degrees latitude, can be taken as about 1 kW/m^2. A fresnel lens of 1000-mm diameter would be adequate even if only one-quarter of the sun's energy in six hours' radiation were transferred to the molten salt. Therefore a lens of considerably under 1000-mm diameter might be found to be adequate. This heat-transfer rate is critical to the design: if the efficiency of heat transfer from solar radiation to the salt is well above 25 percent the size and first cost of the whole cooker would be significantly lower.

Using fresnel lenses

Fresnel lenses formed in plastic sheets have several advantages over mirrors. The hot-plate can be below the lens, on its axis, and no other lenses or mirrors are needed (see figures 4, 5.). The lens could be supported by a strong but low-cost cone of, probably, perforated metal or woven wire that would allow some ventilation and a lower wind resistance while keeping small hands and sticks etc. out of the high-temperature area (figure 5). The light weight and ability to produce a balanced structure would make automatic aiming of the assembly to the sun to be simpler and lower in cost.

The principal present problem with the use of fresnel lenses of the size required is that they are priced at several-hundred dollars each. Our aim for the materials cost of all the components of the cooker is $35.00. However, the costs of manufactured items fall rapidly with the number produced, as shown in figure 6. There is no reason why the future costs of fresnel lenses should not follow the same trends. (An enthusiastic MIT colleague hearing of this need immediately launched a project to make the lenses from discarded plastic (PET) bottles.)

Aiming the lens-and-cooker at the sun

. The preferred solution for timing and aiming the solar cooker at the sun is to use an inexpensive clock mechanism with a balance-wheel (figure 7). This is needed rather than a pendulum because of the different angles at which the mechanism must operate. The spring (which could be a bungee cord or a bicycle inner tube) pulls the swinging frame toward the evening position. Each morning someone pulls the cooker and lens assembly back against the spring (as when winding a clock) until the solar spot is aligned with the target at the center of the hot-plate (figure 3), and released. The clock mechanism starts and maintains alignment for four-to-seven hours. At the end of the desired insolation period, or earlier if a temperature sensor on the pot indicates that all the lithium nitrate is molten, perhaps at 265 C, a latch releases the insulated hot-plate cover to enclose the "thermal battery" totally in low-conductance materials and to prevent further heating (see figure 5.)

Transfer of cooking unit

The thermal-storage unit, including the hot plate, is thus fully insulated and could remain unattended for at least four hours. The concentrator could be swung away (at that time or earlier) and the insulated storage pot could be carried to where it will be used for cooking, outdoors or indoors. For full heat a flat-bottomed pot is put directly on the exposed hot plate. Lesser heat rates can be given by inserting insulating disks under the pot. An oven could also be fitted over the hot plate with a simple adjustable cover limiting the hot-plate exposure. An adapter could also be used to enable traditional round-bottomed pots to be used.

Cooker cost

The total cost for the materials has been aimed at $35. The two major items are the approximately 15 kg of lithium nitrate, which when bought at tonnage levels should be about one dollar per kg., and the fresnel lens. The logic of the cost curves (figure 6) would indicate a cost of under $5 for a fresnel lens of one-meter diameter. A ten-quart (9.5 liter) stainless-steel stockpot can be bought retail for under $10 in the US, so that in lots of tens of thousands they should be under $4. Many of the remaining components of the cooker can be made of low-cost iron, galvanized mild steel, bronze, or coated aluminum-alloy castings, including the hot-plate and connected fins. The insulation around the present hot-plate and molten-salt container is made in foamed-waste glass, for which the cost should be low. For the total to be $35 there may be a degree of optimism, but it is not out of the question. There seems to be no doubt that the monetized accumulated annual benefits of using such a cooker would be considerably higher than the first cost.

ANTICIPATED CHALLENGES (TASKS)

1. The optimum hot-plate material and configuration need to be chosen. The obvious candidates are copper, bronze and coated aluminum alloys (for high conductivity) and cast iron (for low cost.) The possibility of interaction with lithium nitrate is a factor to be considered, though it has been thoroughly researched earlier without problems being found except for uncoated aluminum. The absorptivity and emissivity of concentrated solar radiation must be optimized (Kennedy, ref. 8). Special materials could be used in the target areas. Most of this task would be carried out by analytical modeling but tests would be carried out on different alloys and surface treatments..
2. Degree of concentration: the one-meter-diameter fresnel lens of our present cooker is capable of producing a very intense high-temperature spot of a few millimeters diameter that can melt some metals. Analysis and experiments are needed to determine if the lens should be displaced a few millimeters out of focus to broaden the area of intense radiation and to decrease its temperature.
3. The target point of the focused radiation is, in the present cast-iron hot plate, a series of three deep vee-shaped grooves at the center (figure 3). This must be confirmed as an acceptable choice, or modified. .

4. After the cooker angle is adjusted for sun position, presumably required every few days, the cooker will swing about a single axis (figure 3) and the timer should keep the focused spot within a few millimeters of the center of the hot plate for the succeeding seven hours. The timer must operate in sun and shade, dry conditions and rain, without requiring water or sand or batteries. A clockwork controller of the scale used for grandfather clocks seems most appropriate (figure 7), but this must be confirmed. An alternative is a ratcheting drive powered by the off-center spot hitting, e.g., liquid-filled tubes that would vaporize and thus expand bellows to bring about renewed centering of the spot.
5. The overall design of the solar stored-heat cooker must be produced so that it will be easy and enjoyable to use, perhaps under a village tree, or taken into a building for family cooking, after the thermal battery is charged. Such a cooker could become a status symbol and be a desirable item to steal, which therefore should be made difficult. It should present no danger to children or animals. If a violent hailstorm damages the lens, it should be replaceable at low cost.
6. The solar cookers should be tested in realistic conditions in tropical villages.
7. After an initial trial period and subsequent incorporation of recommended improvements, the cookers should be capable of being produced and serviced locally. We have considered that two or three stages of trials, using increasing numbers of cookers in different areas, would be desirable.

A group from an enthusiastic class on entrepreneurship produced a beautiful, somewhat fanciful, video of the solar cookers being used in Nigeria. The video is listed as Ham et al, reference 9.

CONCLUDING REMARKS

This has been a brief report on a type of solar cooker that could bring about huge benefits to the welfare and health of poor people in tropical parts of the world and would also remove a major cause of desertification and of carbon-dioxide production. It is vitally necessary that its operation be simple and reliable for long periods and that local businesses be trained to provide assembly, installation, maintenance and repair. Most tropical regions have fairly short rainy seasons, during which time stoves needing fuel will still be needed. Low-emission high-efficiency stoves are under widespread development (Global Alliance for Clean Cookstoves, Washington DC)

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TABLE I
THERMAL-STORAGE PHASE-CHANGE MATERIALS

INORGANICS	MATERIAL	M.P. (C)	HEAT OF FUSION, kJ/kg	MASS NEEDED kg
	Bismuth	271	50.2	108
	Iron chloride	304	126	43
	Lithium nitrate	250	367	15
	Potassium nitrate	338	118	46
	Rhenium pentoxide	296	126	43
	Sodium nitrate	310	185	29
	Tin	232	60	90
	Zinc chloride	283	170	32
ORGANICS	pChlorobenzoic acid	240	206	26
	pNitrobenzoic acid	239	221	24
	Carbazole	243	176	31
	Anthraquinone	285	157	35
	Anthracene	216	162	33

FIGURES

Figure 1 The VITA solar cooker

Figure 2. ***Stainless-steel 7-6-liter stockpot and finned underside of solid-copper hot-plate that together form a sealed container for molten salt***

Figure 4 Three-degree-of-freedom frame built to test the performance of a plastic-sheet fresnel lens, which is on top, facing toward us. The lens and its support and the attached hot-plate and storage pot all swing on bearings, one of which is visible on the left side of the sloping frame. The basic, lower, frame is level and aligned accurately north (towards us) and south. The frame is adjusted to the sun's path at this latitude (42.3 degrees N) and time of year. The lens assembly has bicycle-inner-tube springs pulling it toward the afternoon position. The assembly is restrained by a clock movement so that it is aligned with the sun's position from the morning whether or not there are clouds.

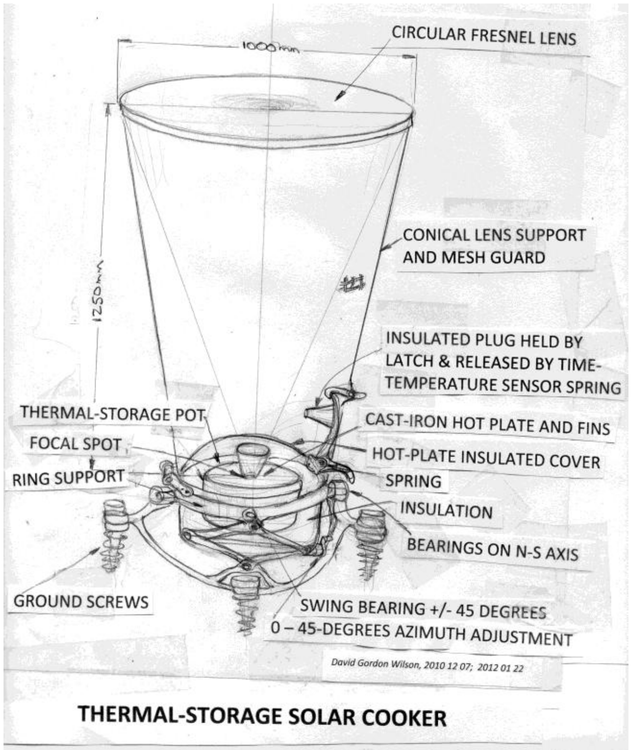

Figure 5. Present (2013) concept of thermal-storage solar cooker

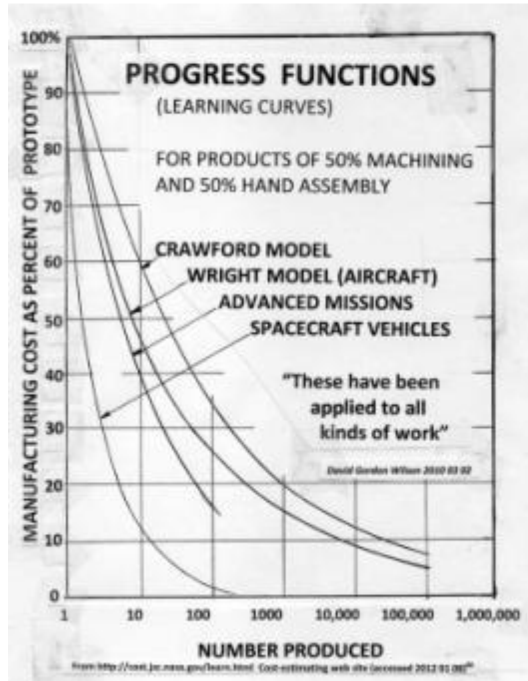

Figure 6. Typical cost curves (from NASA)

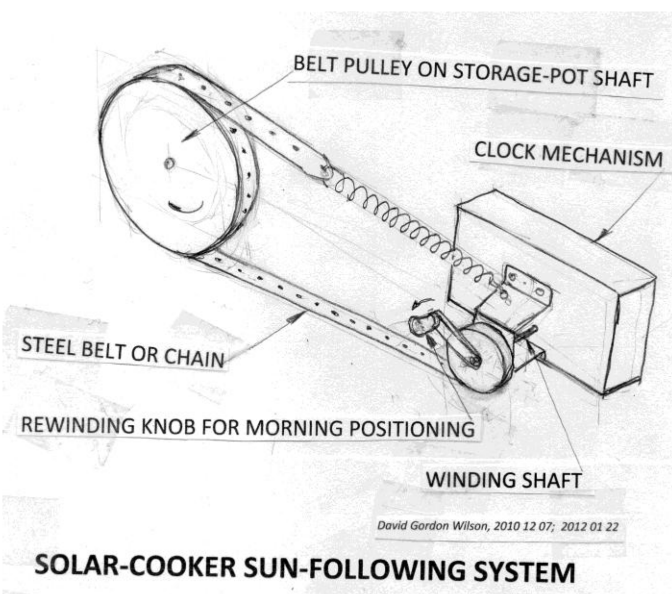

Figure 7. Open-loop sun-following timer