# Solar Box Cooker for Gujarat, India


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## ABSTRACT

In recent decades, there has been a push by local banks, NGOs, and the Indian Renewable Agency Development Agency (IREDA) to introduce solar box cookers (SBCs) into the market in India (Pohekar et al., 2005). Most regions of the country receive nearly 275 days of sunlight and experience solar radiation at a level of 5-7 kW h/$m^2$ (Pohekar et al., 2005). Drivers such as the fuel shortage in India (Pohekar et al., 2005), health impacts from burning biomass (WHO, 2007), and the impact on global warming resultant from black carbon (Zender, 2007) indicate the importance of using renewable energy for cooking. Despite these arguments, only 5.3 million SBCs have been sold through December 2002 (Pohekar et al., 2005). The main goal of this study was to improve the design of the solar box cooker to make it more relevant, intuitive, and user friendly to the emerging middle class, rural households in Gujarat, India. This goal was aimed at spurring adoption of the solar box cooker so that these households can reduce their reliance on nonrenewable fuels, but not substantially change their way of life. Despite uncertainties in the modeling and prototyping we have determined that there are feasible ways to reduce cost while maintaining equivalent or improved performance. Further research should be performed to create a solar box cooker design that is cost-effective, sustainable, and fits the needs of the user. This design can result from either one of two paths, costing down the current solar box cooker design or creating an innovative new design.

In recent decades, there has been a push by local banks, NGOs, and the Indian Renewable Agency Development Agency (IREDA) to introduce solar box cookers (SBCs) into the market (Pohekar et al., 2005). At a glance, India appears to be an ideal market for these solar cookers. Most regions of the country receive nearly 275 days of sunlight and experience solar radiation at a level of 5-7 kW h/$m^2$ (Pohekar et al., 2005). Drivers such as the fuel shortage in India (Pohekar et al., 2005), health impacts from burning biomass (WHO, 2007), and the impact on global warming resultant from black carbon (Zender, 2007) indicate the importance of using renewable energy for cooking. Despite these arguments, only 5.3 million SBCs have been sold through December 2002 (Pohekar et al., 2005). The main goal of this study was to improve the design of the solar box cooker to make it more relevant, intuitive, and user friendly to the emerging middle class, rural households in Gujarat, India. This goal was aimed at spurring adoption of the solar box cooker so that these households can reduce their reliance on nonrenewable fuels, but not substantially change their way of life.

*Background*

To better inform our approach to this project, a literature review was performed to determine background information on our target population in Gujarat, India, including fuel usage, common foods, and so on. A competitive analysis on a number of commercial solar cookers was conducted and a number of user interviews were given. The literature review indicated that India is home to over one third of all the poor people on our planet, with a higher percentage of the population living on less than $2 per day than even sub-Saharan Africa – 75.6% compared to 72.2% (TNN, 2008). Energy for cooking comprises 90% of total household energy consumption in India (Pohekar et al., 2005). The high-energy requirements are in part due to the widespread usage of traditional low-cost devices called *chullas* (cook-stoves) among the rural masses (Pohekar et al., 2006). However, although, Solar Cookers International has rated India as the number one country in the world in terms of solar cooking potential (SCI, 2004), it is evident from Pohekar and Ramachandran's study that there are still significant hurdles for the product in face of mass adoption. These barriers include technical limitations and the lack of commercial infrastructure (Pohekar et al., 2006).

*Methodology*

**Solar box cooker thermal and cost modeling**

The main goal of the study was to help build the tools necessary to compare the performance and cost of solar box cooker (SBC) designs, which will then inform future prototypes. The models were based on a commercially produced solar box cooker manufactured by Fair Fabricators. Scenarios were chosen, altering only one major solar box component at a time to determine both performance and cost benefits of the changes. After reviewing the results, combination scenarios were created to test the performance and cost of altering multiple solar box components concurrently. This assessment focused on material costs and the following efficiency parameters: peak temperature, rise time for the temperature inside the SBC to reach pasteurization temperature (176 ºF), and length of time above the pasteurization point.

**Concept Development and Prototyping**

The methodology put in place for concept development was designed to effectively translate need-finding data into high performing solutions. Brainstorming was approached with the goal of generating as many disparate concepts as possible. Eventually these concepts were channeled into low cost solutions. Prototypes developed include a minimalistic cardboard cooker, lunch box cooker, plastic molded cooker, and flat-pack cooker. All prototypes underwent stagnation tests to be assessed in comparison to the commercial cooker. Performance was judged with the same parameters as the thermal model.

*Results and discussion*

**Solar box cooker thermal and cost modeling**

Despite uncertainties in our model assumptions and prototyping tests, the thermal and cost models as well as the prototyping concepts provide a good foundation for future groups. The results imply window construction can greatly impact solar box cooker performance, providing the main conduit for heat loss. Box shell material can be exchanged for cheaper materials because the material has negligible impact on performance. However, while the box material and insulation have positive cost savings from the benchmark model, any changes to the window component significantly drove up the cost. Given this price variability, a better understanding of user requirements for performance, their pricing sensitivity, and material availability in India is vital to future progress. If demand is elastic and consumers will only pay a certain price for the product, then it may be best to rely on cheaper and less-efficient window options.

**Prototyping**

All tested prototypes are feasible as low cost box cookers, maintaining temperatures above 176°F. The cardboard cooker had decent performance but suffered from material degradation over the course of one day. Material changes would have to occur for this to be a sustainable product. The lunch box cooker performed well, even in comparison to the commercial box cooker. The next step in development is to design for manufacturing. The plastic cooker performed well while suffering no structural deterioration due to heat. The glass window as opposed to the acrylic window only showed an increase in performance of about 10°F. The flat pack cooker showcased mediocre performance. Poor heat retention abilities were observed due to improper sealing and ineffective insulation. All concepts show promise but require more development.

*Conclusions and Recommendations*

Over the course of this project, a number of roadblocks to further generation of solar box cookers were encountered. However, the possible benefits in spurring mass adoption of solar box cookers are large, including improvements in health and economic status. Therefore, we believe that further research should be performed to create a solar box cooker design that is cost-effective, sustainable, and user-friendly. This design can result from either one of two paths, costing down the current solar box cooker design or creating an innovative new design. Both of these paths require a more broad knowledge of appropriate materials that could be utilized in creative ways in solar box cooker construction. Most importantly, we recommend future steps include field research in Gujarat, India. Information including user needs, local materials, and local manufacturing processes are necessary to inform future design and adoption.

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**Scope of Problem**

In recent decades, there has been a push by local banks, NGOs, and the Indian Renewable Agency Development Agency (IREDA) to introduce solar box cookers (SBCs) into the market (Pohekar et al., 2005). At a glance, India appears to be an ideal market for these solar cookers. Most regions of the country receive nearly 275 days of sunlight and experience solar radiation at a level of 5-7 kW h/$m^2$ (Pohekar et al., 2005). Despite these advantages, only 5.3 million SBCs have been sold through December 2002 (Pohekar et al., 2005). This project's challenge is to revisit the SBC design and make improvements to the materials and efficiency while lowering the upfront cost.

*Energy Ladder*

The type of cooking fuels used in each household depends largely on income and location. According to Gupta and Ravindranath, cattle dung, crop residue, and fuelwood are important cooking fuels in residential sectors only for low-income households (Gupta & Ravindranath, 1997). The market share for these fuels drops dramatically as income increases, shifting towards kerosene and LPG (Liquefied Petroleum Gas) (Gupta & Ravindranath, 1997). The Indian Government has also been encouraging this shift to kerosene and LPG by offering subsidies for each cooking fuel (Malhotra, 2008). Kerosene is priced at 69% of the production and supply cost while LPG is kept at 61% of the actual cost (Malhotra, 2008). Despite these subsidies, the rural population still depends heavily on fuelwood due to high initial costs for fuel and a poor kerosene/LPG supply chain (Malhotra, 2008). Furthermore, the government does not control fuelwood distribution and rural consumers can pay more than the government's controlled rates (Malhotra, 2008).

*Fuel Shortage*

In India, the domestic sector accounts for nearly 40% of the country's total energy consumption. Of this household demand, 90% of the energy is consumed solely for cooking (Pohekar et al., 2005). In concurrence with the increasing population, this energy demand for cooking is increasing at an alarming rate of 8.1% each year (Pohekar et al., 2005). Thus, the combined effect of the increasing population and cooking energy consumption has created a widening gap between energy supply and demand (Pohekar et al., 2005). Despite this energy shortfall, the Indian population remains heavily dependent upon nonrenewable sources for cooking energy (Pohekar et al., 2005).

Most market studies show that the type of cooking fuel used in households depends largely upon income and/or location (Pohekar et al., 2005). For example, the middle class relies primarily upon kerosene in urban areas and firewood in rural areas (Pohekar et al., 2005). However, regardless of location, the higher income class largely prefers liquefied petroleum gas (LPG), while the lower class mainly gathers firewood or cattle dung (Pohekar et al., 2005). Though there has been increasing substitution of biomass with commercial fuels nationally, this trend has had negligible impact in rural areas (Malhotra, 2008).

*Burden of Collecting Fuelwood*

Traditionally, the burden of collecting fuelwood falls to women and children in poor rural households. In Gujarat, India, 65% of rural households rely on firewood as their primary cooking fuel source, with crop residue as their secondary source at 13% (India Stats, 2001).

A 1986 study by Bina Agarwal reveals that in the severely depleted forest areas of Gujarat, women and children spent up to five hours a day, traveling between 4 to 10 kilometers to collect cooking fuel (Sen, 2003). This activity needs to be repeated every four days in forested areas, or daily in depleted areas (Sen, 2003). Given the 20+ year span since Agarwal's research was published, it is highly likely that today women are traveling further distances for longer periods of time on a more frequent basis.

*Health Risks – Indoor Air Pollution*

Cooking and heating with solid fuels (biomass such as firewood, cattle dung, and crop residue; coal) on open fires or traditional stoves results in high levels of indoor air pollution. In particular, biomass combustion contains many health-damaging pollutants, such as particulate matter and carbon monoxide (WHO, 2007). Particulate matter has long been associated with increased risk for serious respiratory and cardiovascular health problems. Key effects associated with exposure to ambient particulate matter include: premature mortality, aggravation of respiratory and cardiovascular disease, aggravated asthma, acute respiratory symptoms, chronic bronchitis, decreased lung function, among others (US EPA, 2009). In low-income countries, lower respiratory infections are the second leading cause of death (WHO, 2007).

*Global Warming*

Black carbon is generated by combustion of fossil fuels, biofuel, and biomass (Zender, 2007) and has recently emerged as the second largest contributor to rising global temperature after carbon dioxide (Rosenthal, 2009). Black carbon, or soot, is responsible for 18% of global warming (Rosenthal, 2009) as black carbon absorbs heat in the atmosphere and reduces the ability to reflect sunlight when deposited on snow and ice (Zender, 2007). Unlike carbon dioxide that remains in the atmosphere for many decades, black carbon tends to settle within a week of its emission (Zender, 2007). But during that week, a black carbon particle can circulate, with soot from India to the Maldives Islands and on the Tibetan Plateau (Rosenthal, 2009). It is estimated that 40% of the annual global emissions of black carbon are due to open biomass burning (Ramanathan, 2008).

**Statement of Goals**

This semester, the solar box cooker project began as a new idea without any work from previous groups. To begin the project, our group worked to narrow our focus by developing comparisons between various options. These comparisons, included in Appendix A, listed the pros and cons for design considerations including target demographics, solar cooker technology, and price point. From these comparisons, our group decided to design a solar box cooker for the rural, emerging middle class in Gujarat, India. Following the narrowed focus, our team set goals for the semester that included drafting a prototype, documenting the design's limitations, investigating cultural barriers to adoption, producing detailed CAD/CAM drawings of the cooker, and developing a business plan for mass production in India. However, we ran into several roadblocks and restructured our goals. The first roadblock involved the market saturation of SBCs in India. The second roadblock involved the decision to pursue either a radically new design or an improvement on the commercial device. Finally, local contacts in India have been difficult to establish and strengthen. In response to these roadblocks, our team decided to split into two groups to focus on both the new design and improved commercial design. A diagram of the team structure is included in Figure 1.

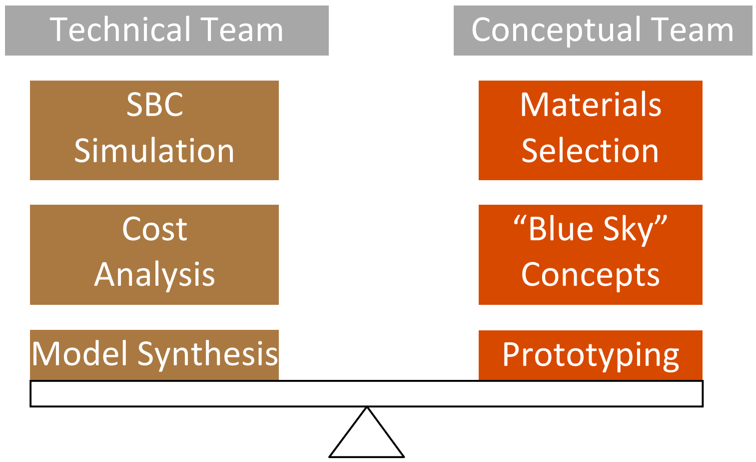


**Figure 1. Team structure**

Cindy Chen and Joy Wei formed the technical team to address the improvement of the commercial design. This design has been used since the 1970's and has not adopted simple material changes. The technical team addressed this problem by developing economic and thermal models to represent the commercial design's cost and performance. These models could then track the changes in cost and performance as new materials were introduced to the commercial design. Nivay Anandarajah and Andy Torkelson formed the conceptual team to concentrate on new approaches to the design. After brainstorming sessions, the conceptual team designed and built several prototypes to test their performance against the commercial design. Ultimately, the Solar Box Cooker team strove to determine valuable background information, thermal/cost models, conceptual prototypes, and contacts that can be used as a strong base for the work of future groups.

In summation, our team goals for the semester were as follows:

- To improve the design of the solar box cooker to make it more relevant, intuitive, and user friendly to the emerging middle class, rural households in Gujarat, India.
- To spur adoption of the solar box cooker so that these households can reduce their reliance on nonrenewable fuels, but not substantially change their way of life.
- To provide future groups with the necessary information and tools to conduct on-the-ground research on solar box cooker adoption in Gujarat, India.

To better inform our approach to this project, a literature review was performed to determine background information on our target population in Gujarat, India, including fuel usage, traditional foods, cultural practices, and more. We also performed a competitive analysis on a number of commercial solar cookers. To better understand the experience of current and past solar box cooker users, we conducted several user interviews in person and remotely.

**Target Population – India**

India is home to over one third of all the poor people on our planet, with a higher percentage of the population living on less than $2 per day than even sub-Saharan Africa – 75.6% compared to 72.2% (TNN, 2008). The World Bank's Poverty report indicated that the number of poor people living under $1.25 a day has increased from 421 million in 1981 to 456 million in 2005, implying that there are "a large number of people living just above this line of deprivation and their numbers are not falling" (Chen et al., 2008).

Energy for cooking comprises 90% of total household energy consumption in India (Pohekar, 2005). The high-energy requirements are in part due to the widespread usage of traditional low-cost devices called *chullas* (cook-stoves) among the rural masses (Pohekar, 2006). Chullas are inefficient and require copious amounts of fuel-wood (Pohekar, 2006). There is a huge opportunity for more efficient and/or renewable domestic cooking devices. Solar Cookers International has rated India as the number one country in the world in terms of solar cooking potential (SCI, 2004).

*Sub-population - Gujarat*

Gujarat is the westernmost state in India with mild, dry winters and hot, dry summers (Gujarat, n.d.). The region has ideal solar energy conditions, "with almost 300 days of clear sun, strong radiation, conducive arid conditions, and minimal sun tracking" (Dave, 2008). Gujarat will be the first state to set up solar power plants in the country (Dave, 2008) and is already home to six manufacturers of solar cookers (GEDA, n.d.). Regional cuisine in Gujarat is also favorable to solar cooking. Gujarati cuisine is primarily vegetarian, consisting of rice, daal, sabi/shaak (a dish of vegetables and spices), and roti (flat bread made from wheat flour) (Gujarti cuisine, n.d.). All of these main dishes, with the exception of roti, can be cooked in a solar box cooker.

**History of Solar Cooking in India**

Solar cookers were first introduced to India in the early 1980s. In 1984, the Ministry of Non-Conventional Energy Sources (MNES) began a subsidy program to spur adoption of solar box cookers (Kumar, n.d.). During this period, an estimated 5.4 million solar box cookers were sold or installed in India (Kumar, n.d.). However, these numbers may not reflect the true number of solar box cookers in use, as “most people abandoned [the solar cookers]” because there was “no follow up, no after sales service, no networking.” (Narayanaswami, Mar 2001). MNES promoted the solar box cookers as a product, not as a new process for cooking that required behavioral change. By 1994, MNES withdrew the solar box cooker subsidy, although Gujarat and Karnataka continued the subsidy program (Narayanaswami, June 2001). The India Government and MNES continue to promote renewable energy projects, but with a focus on high-tech devices such as wind energy and photoelectricity (Narayanaswami, June 2001). The Indian government heavily subsidizes non-renewable energy sources like kerosene and LPG as well (Srinivas, 2008).

**Substitute Cooking Devices**

Socio-economic and climate factors play a large part in determining what types of cooking devices are used in different populations in India. In Pohekar and Ramachandran’s white paper on the utility assessment of domestic cooking devices in India, 9 popular cooking devices are evaluated against 30 criteria covering technical, economic, behavioral, and commercial issues. LPG stoves bring the highest utility to users, followed by microwave ovens, kerosene stoves, electric ovens, parabolic solar cookers, biogas stoves, improved chulhas, solar box cookers, and traditional chulhas (Pohekar, 2006).

Table 1 illustrates how solar box cookers compare to the best and worst options (LPG and traditional chulhas, respectively). The “winner” was determined by choosing the device with the highest utility value for each criterion.

It is evident from Pohekar and Ramachandran's study that while the solar box cooker excels in reducing fuel costs and pollution hazards, as well as improving the quality of food, there are still significant hurdles for the product. These barriers include technical limitations and the lack of commercial infrastructure (Pohekar et al., 2006).

**Table 1. Device with highest utility**

| No. | Criteria | "Winner" |
|---|---|---|
| **Technical** | | |
| CR 1 | Fuel consumption | SBC |
| CR 2 | Cooking time | LPG |
| CR 3 | Durability | SBC |
| CR 4 | Quality, reliability | LPG |
| CR 5 | Sophistication level | LPG |
| CR 6 | Size/weight | Chulha |
| CR 7 | Ruggedness | Chulha |
| CR 8 | Continuity of use | LPG |
| CR 9 | Need for tracking | Chulha |
| CR 10 | Nutrition value of food | SBC |
| **Economic** | | |
| CR 11 | Initial cost | Chulha |
| CR 12 | Fuel cost per month | SBC |
| CR 13 | Maintenance cost per year | Chulha |
| CR 14 | Available subsidy | SBC |
| CR 15 | Rate of interest on loan | Chulha |
| **Behavioral** | | |
| CR 16 | Pollution hazards | SBC |
| CR 17 | Human drudgery | Chulha |
| CR 18 | Overall safety | SBC |
| CR 19 | Aesthetics | LPG |
| CR 20 | Motivation to buy | LPG |
| CR 21 | Taste of food | SBC |
| CR 22 | Cleanliness of utensils | SBC |
| CR 23 | Ease of operation | LPG |
| CR 24 | Type of dishes cooked | LPG |
| CR 25 | Need for additional cooking system | LPG |
| **Commercial** | | |
| CR 26 | Improvement in models | LPG |
| CR 27 | Spares and after sales service | LPG |
| CR 28 | Distribution network | LPG |
| CR 29 | Market research | LPG |
| CR 30 | Need for user training | Chulha |

**Competitive Benchmarking**

There are over 70 different commercial manufacturers of solar cookers, not including cardboard-tinfoil DIY models (SCI, n.d.). In India alone, there are 12 manufacturers primarily located in northern India (SCI, n.d.). Wholesale unit prices vary from US $15 for a cardboard model to US $150 for a mass-produced solar box cooker with four reflectors (SCI, n.d.). Given the substantial variation in design, features, and materials, we conducted a competitive analysis of 16 different solar cookers (both parabolic and solar box cooker). The results are listed in Appendix B.

**Primary Interviews**

Primary interviews were performed to help identify solar box cooker users' needs. The method of open-ended interviews was chosen to allow users to freely tell their stories, shedding usability insights along the way. Please see Appendix E for a list of interview questions used during our primary interviews. However, due to geographic constraints, we were unable to perform ground interviews. Individuals who previously used solar box cookers in India but currently lived near Berkeley, CA were found instead. This unfortunately confined the socio-economic status of the user group. Despite this constraint, the interviews provided valuable insight into the use of solar box cookers in India and the possible areas for improvement. In general, the solar box cooker was described as a supplementary device used for cooking rice, daal, and pastries. Each user expressed a fondness of the food prepared in the solar box cooker, but lamented the variation in cook time from day to day. The users were attracted to the device through government promotion and environmental awareness. Finally, each user felt the solar box cooker could be improved by reducing cook times, including temperature indicators, easing access for tasting, and increasing protection from burns. A list of key insights and interpreted needs from each interview are listed in Table 2.

**Table 2. Key insights and interpreted needs from user interviews**

| User | Key Insights | Interpreted Needs |
|---|---|---|
| Anjali (2009) | - The cooker was used as a supplementary device for rice in conjunction with a gas stove.<br>- The cooker remained stationary outside most of the time.<br>- She had to open up the tin and check to see how the food was cooking often.<br>- The outside plate could get very hot sometimes (gloves had to be used).<br>- Food was primarily served in the center of the house. | - The cooker should be durable enough to stay outside.<br>- The cooker should provide functionality to check food cooking without opening it.<br>- The cooker should have a safe way to open (preventing burns). |
| Maithili (2009) | - The cooker was used primarily by her mother as a supplementary device.<br>- Family became aware of cooker through government promotion.<br>- Family had standard box-type cooker with 4 black pots.<br>- The cooker was not used during the winter but was used 50% of the time during other seasons.<br>- Mother cooked for a family of 3.<br>- Derived some status from owning cooker but she did not like the blue color.<br>- Cooked bread, cakes, jams, rice, and daal. | - Experience was required to tell if food was ready.<br>- Time to finish could vary widely between days.<br>- Requires a significant change to daily schedule.<br>- Mother had to plan meals in advance.<br>- Cooker is too expensive without subsidies. |
| Murthy (2009) | - There were many challenges during self-construction (sealing, finding proper insulation, finding nontoxic paint).<br>- The commercial Cookit and Global Sun Oven were very fast but very expensive with marginal gains.<br>- A variety of foods were eventually tried (nuts, pastries, traditional foods).<br>- Sunglasses were worn for eye protection.<br>- The metal handle would get deceptively hot<br>- Sometimes the cooker would fog up preventing it from getting as hot. | - The low fidelity cooker should have easier assemblage.<br>- Included information should describe the variety of foods that can be cooked.<br>- The cooker should protect the eyes.<br>- The cooker must prevent condensation from forming. |

**SBC Thermal and Cost Modeling**

*Goal and Scope Definition*

The main goal of the study was to help build the tools necessary to compare the performance and cost of solar box cooker (SBC) designs, which will then inform future prototypes. The models were based on a commercially produced solar box cooker lent to the team by Professor Gadgil (see Figure 2 to the right) (Solar Cooker Review, 2009). The manufacturer for this solar box cooker is Fair Fabricators, based in Indore, India. Then scenarios were chosen, altering only one major solar box component at a time to determine both performance and cost benefits of the changes. After reviewing the results, combination scenarios were created to test the performance and cost of altering multiple solar box components concurrently. This assessment focused on material costs and the following efficiency parameters: peak temperature, rise time for the temperature inside the SBC to reach pasteurization temperature (176 ºF), and length of time above the pasteurization point.

**Figure 2. Typical solar box cooker**

*Functional Unit*

The functional unit for this study was one solar box cooker. The base model, Scenario A, was taken to be the Fair Fabricators commercial solar box cooker. All subsequent solar box cooker design scenarios assumed the same solar box cooker geometry as Scenario A, which can be seen in the Table 2. All solar box cooker scenarios also assumed the presence of only one reflector.

**Table 2. Solar box cooker dimensions**

| Dimension | (in) |
|---|---|
| height of reflectors, h | 22 |
| width of outside box, wo | 22 |
| length of outside box, Lo | 22 |
| width of inside box, wi | 16 |
| length of inside box, Li | 16 |
| depth of box | 4 |

*Components and Materials Studied*

Because the breakdown of a solar box cooker can result in many components, we decided to focus on box shell materials, insulation, window construction, structural materials, and reflectors. A list of considered materials for each of these components can be found in Table 3. We decided to focus on the above categories because the exclusion of any would result in an inaccurate representation of total cost; however, structural materials were not included in the stagnation model because it would likely have no effect on the thermal capabilities of the solar box cooker. The materials chosen for each component were considered to be representative of broad material categories that are commonly used for solar box cooker construction.

*Scenarios*

Several scenarios were created to better understand the relationship between material choice and performance and cost. Please see Table 4 for material assignations for all scenarios. Scenario A was our baseline scenario, describing the basic materials used in the Fair Fabricators SBC. Here, scenario A contained aluminum sheet metal as the box shell material, fiberglass as insulation, and a double pane window with 0.1875" air space as the window construction. Then, to better understand how individual components affected price and performance, scenarios B through H only altered one component at a time. After results were calculated for the aforementioned scenarios, performance and price for each scenario was compared with that of our baseline scenario and then combination scenarios I and J were created to provide an understanding of how a combination of component alterations would affect efficiency and cost.

SBC stagnation model performance was defined by three results: peak temperature ($T_p$), rise time of the temperature inside the SBC to the pasteurization point, 176 ºF ($t_r$), and length of time the temperature inside the SBC stayed above 176 ºF ($t_{length}$). Please see Figure 3 for term clarification. Cost was defined by initial material costs. Assumptions that went into determining performance and cost will be discussed in the following sections.

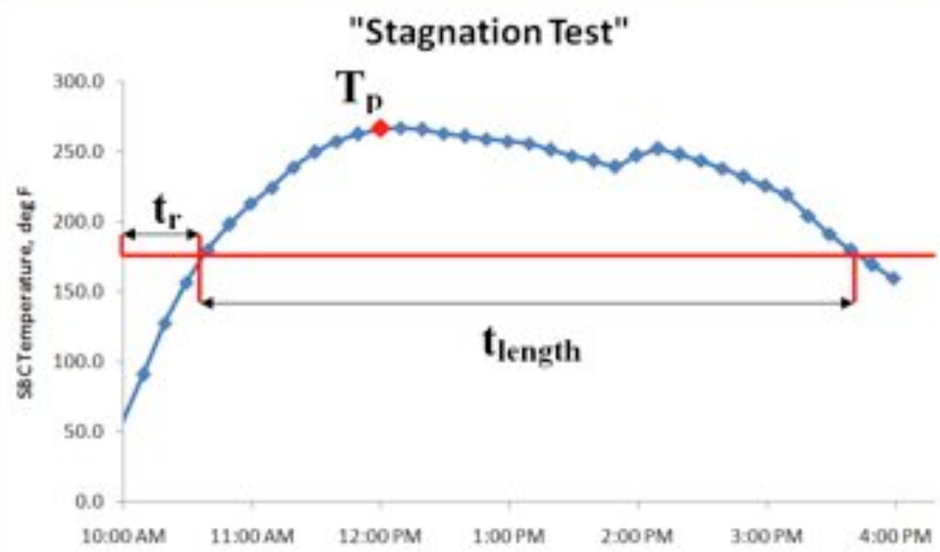


**Figure 3. Stagnation model efficiency parameters**

*Stagnation Test*

To verify the results of the thermal model, a stagnation test was performed on March 20, 2009. The test began at 11:45 AM and ran until 3:40 PM. Thermocouples were used to determine the temperatures inside and outside the solar box cooker. Data was collected every ten minutes to ensure a reasonable stagnation curve.

*Thermal Model*

The stagnation model solves for the temperature inside the solar box cooker by solving the energy rate equation:

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{acc}$$

Where $\dot{Q}_{in}$ is the heat gain term [W], $\dot{Q}_{out}$ is the heat loss term [W], and $\dot{Q}_{acc}$ is the heat accumulation within the SBC term [W].

The heat gain term is calculated as

$$\dot{Q}_{in} = \left(A_{refl} + A_{window}\right) * S * \sin(\beta)$$

Where S is the solar radiance [W/m$^2$], β is altitude [$^o$] and $A_{refl}$ and $A_{window}$ [m$^2$] represent the amount of solar radiation (indirect and direct, respectively) the window of the SBC is exposed to. The solar radiance is multiplied by the sine of the altitude to take into account the amount of

**Table 3. Basic solar box cooker components and materials**

| SBC Component | Materials | Considered in stagnation model? | Considered in cost analysis? |
|---|---|---|---|
| Box shell | Aluminum sheet metal<br>Plywood (sand fir)<br>Hardboard – high density | Yes | Yes |
| Insulation | Fiberglass<br>Foamed plastic – polystyrene<br>Spray applied – polyurethane foam | Yes | Yes |
| Window construction | Double pane<br>Double pane with low-e coating<br>Triple pane | Yes | Yes |
| Structural material | Douglas fir | No | Yes |
| Reflector | Mirror | Yes | Yes |

**Table 4. Scenario descriptions**

| Scenario | Box shell material | Insulation | Window |
|---|---|---|---|
| A | Al sheet metal | fiberglass | double pane 0.1875" air space |
| B | plywood (Sand fir) - 0.212" x 4' x 8' | fiberglass | double pane 0.1875" air space |
| C | hardboard - high density - 1/8" x 4' x 8' | fiberglass | double pane 0.1875" air space |
| D | Al sheet metal | fiberglass 1" + foamed plastic 2" | double pane 0.1875" air space |
| E | Al sheet metal | fiberglass 1" + polyurethane foam 2" | double pane 0.1875" air space |
| F | Al sheet metal | fiberglass | double glass - 0.5" air space |
| G | Al sheet metal | fiberglass | double glass - 0.5" air space, low e-coating e=0.2 |
| H | Al sheet metal | fiberglass | triple glass - 0.25" air space |
| I | hardboard - high density - 1/8" x 4' x 8' | fiberglass 1" + polyurethane foam 2" | double glass - 0.5" air space |
| J | hardboard - high density - 1/8" x 4' x 8' | fiberglass 1" + foamed plastic 2" | double glass - 0.5" air space, low e-coating e=0.2 |

radiation that falls normal to the window. Currently the model is using an averaged solar radiation data for the month of March as that is when the stagnation test on the commercial SBC was conducted.

The heat loss term is calculated as

$$\dot{Q}_{out} = UA_{eff} * (T_{inside} - T_{outside})$$

Where $UA_{eff}$ is the overall heat loss term for the surrounding walls and the window and $T_{inside}$ and $T_{outside}$ are the temperatures inside and outside of the box. The U-value is a property readily given by most window manufacturers. However, to calculate the U-value for the walls, the R-value (the resistance to heat loss value) was determined for each solar box cooker component, depending on material resistivity and component thickness. The U-Value was then calculated as the reciprocal of the R value. The A term is the respective area through which heat is loss, including the windows, the surrounding walls, and the cooker bottom. $T_{outside}$ is taken from the average temperature in March in San Francisco from 1990-2006.

The heat accumulation term is calculated to be:

$$\dot{Q}_{acc} = TM * \frac{dT}{dt}$$

where TM stands for the thermal mass of the air inside the box as well as half of the box and dT/dt stands for the change in temperature with time. The thermal mass of each component is calculated to be the volumetric heat capacity (VHC) of the material times the volume of the material.

For a more detailed discussion of the assumptions and calculations made in the thermal model, as well as how to use the model, please see Appendix B.

*Cost Analysis*

The cost model estimates the material costs for each scenario, looking at the three primary variable components: box shell material, insulation, and window construction. The structural materials and reflectors were included in the build of materials (BOM) cost but did not vary across the scenarios.

*Thermal model and cost model synthesis*

The results of the thermal and cost models for the combination scenarios were synthesized and then normalized in reference to scenario A. The benchmark scenario, scenario A was given an average rating and subsequent scenarios were rated in reference to scenario A.

**Concept Development**

*Personas*

Successful concept development hinges on the transition between need finding and brainstorming. These following questions were of primary concern during brainstorming:

- Will the needs gathered be forgotten in a hectic brainstorm session?
- Will the concepts accurately reflect a tendency of the target user?

In order to encapsulate the background research, five personas were created. Personas are fictitious characters that allow the designers to act as if they are designing for real people with real problems. It is important to give the personas a complete background because this gives designers the context to imagine real users. By making all the personas sufficiently different, a variety of concepts will be created. With these considerations in mind, five personas were created, as can be seen in Figure 4.

*Brainstorming and Concept Development*

The philosophy adopted for brainstorming was to generate a high number of ideas to ensure that the end product would be the most suitable. For each concept developed, it was important to write down what this concept assumes about the user. For example, a thin-film inflatable cooker assumes the user values portability. This allows for a more considered design, and makes any feedback gathered less arbitrary. Additionally a great amount of sketching occurred, since thinking visually helped the concepts to have realistic physical constraints.

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(from left to right, top to bottom)

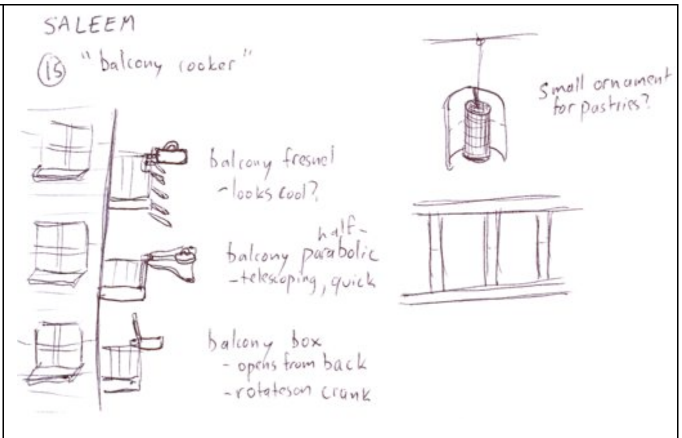
| | |
|---|---|
| **Arundhathi** | A 40 year old stay at home mother of 5 children living in rural areas of Gujarat |
| **Sunjay** | A field worker who has to walk 5 km to his worksite |
| **Manjula** | An 85 year arthritic old woman who tends to a house in an urban area |
| **Saleem** | A 30 year old urbanite working in a box factory who likes to try new things |
| **Shrijitha** | 23 year old widow living in rural areas where she gathers firewood and cow dung for fuel |

**Figure 4. Personas**

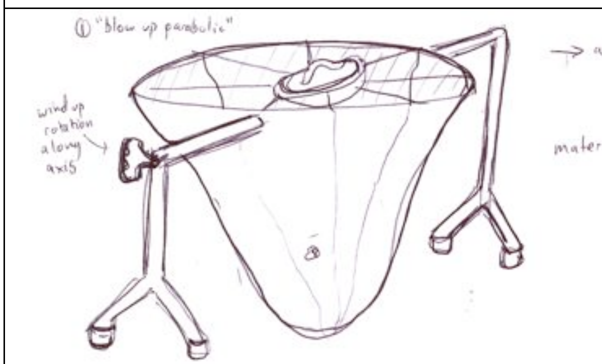
Group brainstorming provided quick idea generation, allowing designers to draw from their own, as well as each other's, background. A formal brainstorm session was conducted on March 6th, 2009 where many of the participants were from India, making the experience a hybrid activity of need finding and brainstorming. Vijesh, a student from India, provided great insight suggesting solutions for field workers, cooking as a private activity, and portability for street vendors. Cardboard was provided to create low fidelity prototypes to help visualize solutions. In addition to the formal brainstorming session, Howdy Goudey and Jonathan Slack of Lawrence Berkeley National Laboratory (LBNL) labs provided technical guidance and inspiration. Based off of their knowledge of heat transfer, novel methods of heat capture and heat retention were created. These solutions provided a jumping point for more developed concepts.

Individual brainstorming was also conducted. The first round of individual brainstorming led to solutions reflecting the personas created. Some concepts generated can be seen in Figure 5. The second round of brainstorming focused on reducing the cost of the cooker. Solutions include an exploration of innovative materials and manufacturing methods.

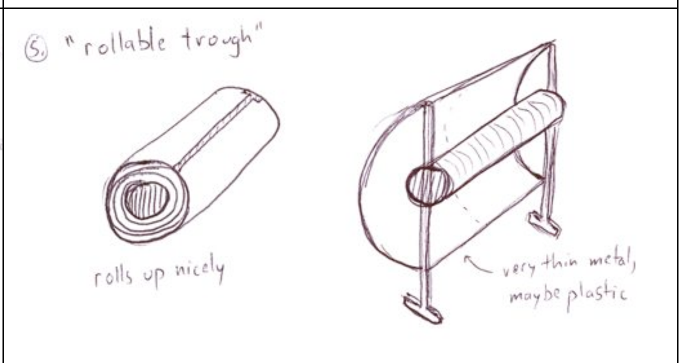

**Solar Jacket** – Keeps worker cool while walking and then doubles as a portable cooker




**Balcony Cookers** – Box and parabolic cookers modified for the urban environment




**Blow-up Parabolic** – A portable solution that is constructed from thin film plastic and aluminum




**Rollable Trough** – A portable solution that is constructed from thin elastic sheet metal

**Figure 5**. **Concepts Generated**

*Material Selection*

In order to cost down the cooker, innovative new materials were explored. The price point was set so that the box would be as cheap as possible while still exhibiting long-term durability, unlike low fidelity cardboard and aluminum foil solutions. By using insight provided by Howdy

Goudey Jonathan Slack, and Tony Kingsbury, three avenues were explored: plastics, flat-packs, and thin-films.

Plastics

From our competitive analysis, plastics remain largely unused in solar box cooker construction. They are cheap, lightweight, and durable and can be mass-manufactured with ease. Existing tub and bin manufacturing plants can be retrofitted to make solar cookers. Plastics have potential to act as box structure, box insulation, box reflectors (with additives), and box windows. Polyurethane is the plastic that is most appropriate for the specifications.

Flat-pack

Flat-pack style materials can be easily disassembled and collapsed into a smaller volume to help save costs in transportation and fueling. This idea operates on the assumption that there may be more benefits to manufacture the solar box cookers non-locally and then ship to various suppliers. This could result in flat-pack style materials manifesting as the more sustainable avenue, given high quality control solutions are provided. Flat-packs can be made of corrugated plastics widely used for signage.

Thin-film

Thin-film plastics and aluminum layers have potential in solar cooking to act as the box structure, box insulation, box reflectors and box windows. In addition, they would use an incredibly low amount of material, and can be heat pressed easily. With the proper design, thin films could provide a portable flat-pack solution. The assumption was made that Gujarat is industrialized and has the avenues to locally source these materials. Thin-films can be made from existing Mylar factories and packaging manufacturers.

*Prototyping and Testing*

Prototypes were developed for proof of concept purposes. It was important to see how the materials chosen would function relative to existing solutions. Additionally, for presentation purposes, the concepts could provide good incentive for manufacturers and venture capitalists to invest in this project.

The four prototypes built and tested are outlined in the next two pages in Figure 6.

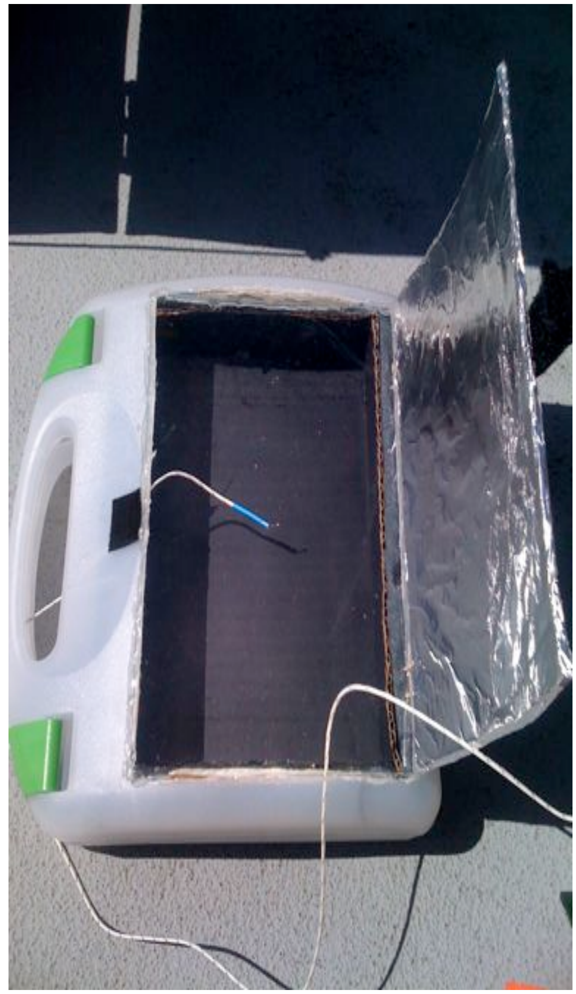
| | |
|---|---|
|  |  |
| **Low Cost Cardboard Cooker** – The device was built with the intention of costing the box down as much as possible using scrap materials. Cardboard, aluminum foil, packaging peanuts and a trash bag were used. Note the trash bag melted due to high temperatures during the stagnation test. | **Lunchbox Cooker** – Serving a niche market of field workers, the lunchbox provides a hot meal for on the go workers. This device places all the typical solar box cooker components in a lunchbox. |

**Figure 6. Prototype designs**

|  |  |
|---|---|
| **Plastic Cooker** – This device uses existing molded plastic as the box structure. The inner tub can be removed for easy transport and cleaning. The model is significantly lighter than the sheet metal alternative. | **Flat-pack Cooker** – By taking advantage of corrugated plastic and Coldpack's packaging liner, a flat-pack solution was created. The cooker can be easily disassembled and flat-packed without tape or glue. The user can then blow up the insulation with a straw. |

**Figure 6 (Cont.). Prototype designs**

The prototypes were tested relative to the performance of the existing commercial solar box cooker. Stagnation tests were conducted for all four prototypes and the commercial solar box cooker on May 7th and 8th, 2009 in Berkeley, CA. Internal temperature for each prototype was recorded every 10 minutes with a thermal couple. In addition, ambient temperature was recorded at similar intervals. By implementing subtle changes in cooker position and reflector angle, operation dependence was evaluated. Additionally, glass is known to trap long wave radiation much more effectively. Therefore, to verify the effect of differing window materials, a plastic (acrylic) versus glass window test was conducted for the plastic cooker on two separate days. On May 7th, the lunch box cooker, low cost cardboard cooker, and plastic cooker were tested. All prototypes on May 7th were fitted with an acrylic window. On May 8th, the flat-pack cooker and plastic cooker were tested. Each prototype on May 8th was fitted with a glass window.

*Concept Selection*

The value added for the concepts was difficult to assess given the array of needs from the target population. The goal of the concept development chain was narrowed to costing down the cooker. The final concepts were evaluated for their ability to provide a low cost solution that didn't degrade over time. The prototypes were assessed for their ability to reach 176 ºF, time above 176 ºF, and maximum temperature. Evaluating the cost of these cookers was difficult given the upfront manufacturing tooling costs. The additional cost of tooling per box can vary immensely based on the scale and infrastructure set.

The two concepts that were capable of fulfilling the goal were the plastic prototype and the flat-pack prototype. The plastic prototype has the possibility of being manufactured for cheap by either retrofitting existing manufacturing plants, or creating a heat forming mold out of wood. The flat pack solution only requires stamping out of corrugated plastic and a partnering with Coldpack for thin-film insulating liners for a low cost solution. Both of these concepts were therefore a promising avenue for the team to move forward with.

The results from the thermal and cost models as well as the stagnation tests from the prototypes are detailed in the sections below. Solution combination scenarios have been compared to the benchmark scenario with marked improvement in performance but differing results in cost. Scenario results can be found in Table 5 and Table 6.

The results from the prototyping stagnations tests are also detailed below. Each concept was assessed for it's ability to reach 176°F, time above 176°F, and maximum temperature. Particular interest was paid to the plastic cooker and the change in performance due to the acrylic/glass window.

**Technical Results**

*Stagnation Test*

To verify the results of the thermal model, a stagnation test was performed on March 20, 2009. The test began at 11:45 AM and ran until 3:40 PM. Results can be seen in Figure 7. The temperature inside the solar box cooker rose to a peak temperature of 229 ºF, had a rise time of 55 minutes to reach temperatures greater than 176º F, and stayed above 176 ºF from 12:50 PM until the test ended at 3:40 PM, almost three hours.

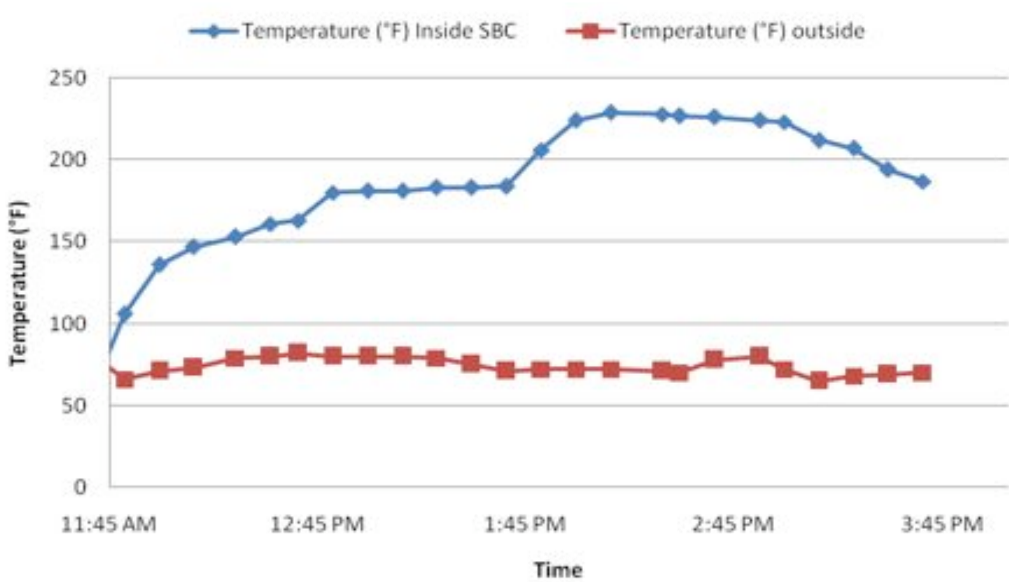



**Figure 7. Stagnation test results**

*Validation of thermal model*

To validate the thermal model results, a baseline scenario based off of the commercial solar box cooker was run, the results of which were compared with the stagnation test results above. The comparison can be seen in the following Figure 8. As can be seen here, the thermal model matches the stagnation test results fairly well, especially in the first half. However temperatures drop off marginally during the second half which may be due to some assumptions and limitations in the model that are discussed further in Appendix C. Therefore, we will assume that the thermal model simulates stagnation tests reasonably well.

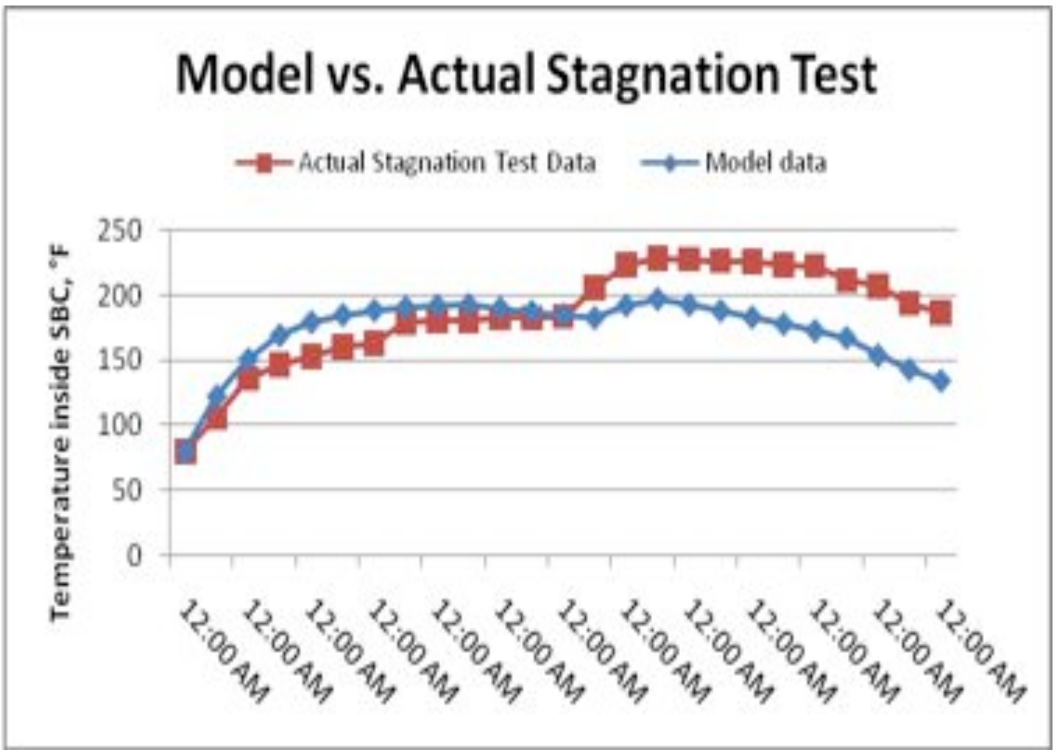



**Figure 8. Thermal model verification with stagnation test results**

**Initial scenarios**

To determine the relationship between material choice and solar box cooker performance, scenarios A-H were run with the thermal model. The results can be seen in Figure 9 through Figure 11 and Table 5.

*Thermal model*

Scenario A is the benchmark scenario with material choices based off of the commerical solar box cooker. The inside and outside material are constructed out of aluminum sheet metal, the insulation is three inches of fiberglass, and the window is a double paned window with an air space of 0.1875”. Scenario A resulted in a peak temperature of 213 ºF, a rise time to 176 ºF of 50 minutes, and a length of time above 176 ºF of 240 minutes.

Scenarios B and C varied the inside and outside box material from aluminum sheet metal to plywood and hardwood, respectively. These two scenarios resulted in little difference in peak temperature, rise time to and length of time above 176 ºF.

Scenarios D and E varied the insulation material from fiberglass to either polystyrene or polyurethane, respectively. Both scenarios use a layer of fiberglass between the inside box material and the second insulation material to shield the second insulation from the high temperatures present at the inside box material surface. Scenarios D and E both show an increase in peak temperature by 20 ºF as well as a longer length of time by 20 minutes that the inside temperature stays above 176 ºF. However neither scenarios demonstrate a decreased rise time to 176 ºF.

Scenarios F through H varied the window construction from a double paned window with 0.1875” air space to double paned window with 0.5” air space, double paned window with 0.5” air space and low e coating, and triple paned window. Scenarios F through H all had marked improvements in performance in comparison with scenario A. However, scenario G resulted in the greatest improvement in performance resulting in a peak temperature of 286.5 ºF, a rise time of 40 minutes, and a length of time above 176 ºF of 310 minutes.

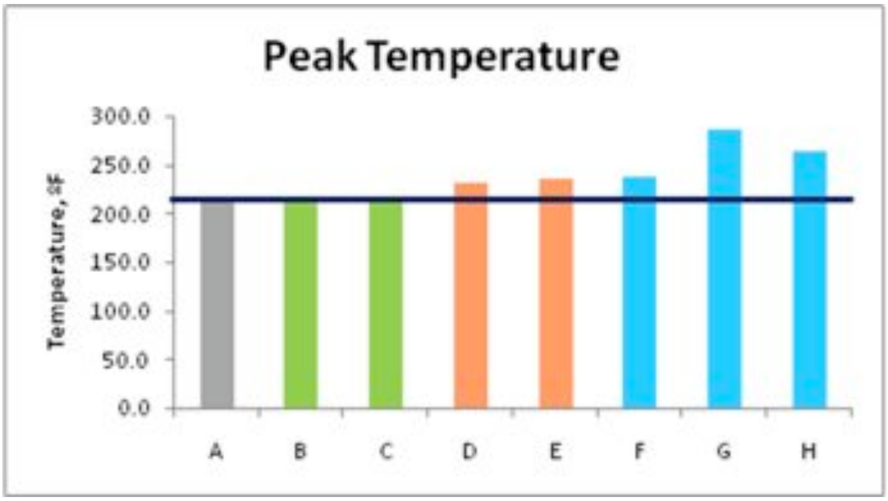



**Figure 9. Initial scenario peak temperature**

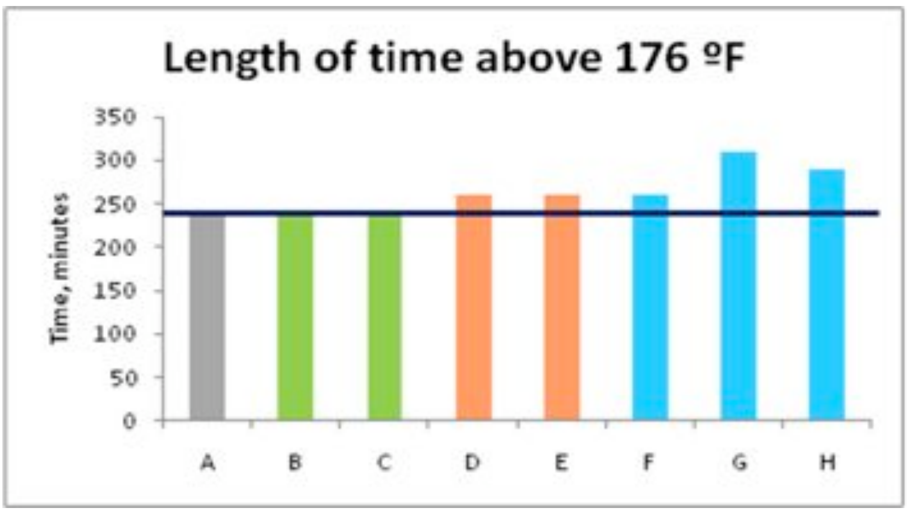



**Figure 10. Initial scenario length of time above pasteurization point**

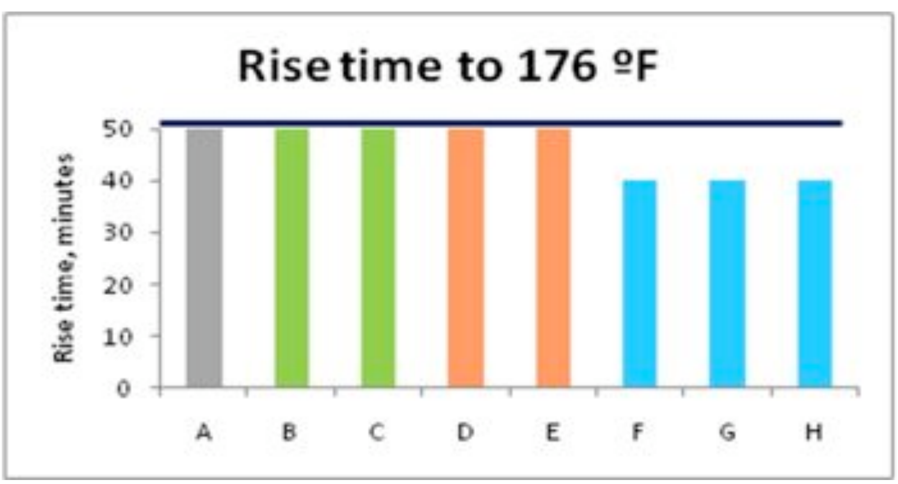



**Figure 11. Initial scenario rise time to pasteurization point**

**Cost Analysis**
Due to the discrepancy between US and Indian prices for raw materials, we chose to compare the relative cost of the different scenarios using scenario A as the benchmark scenario. We then computed the percentage increase or decrease from this benchmark. The results are depicted in Figure 12.

Similar to the thermal model, scenarios B and C varied the inside and outside box material. Changing the box material from aluminum sheet metal to plywood resulted in a 6% cost savings, while changing from aluminum sheet to high-density hardboard had a 14% cost decrease.

Scenarios D and E used different combinations of insulation material. Moving from 100% fiberglass to a combination of fiberglass and polystyrene (scenario D) and fiberglass and polyurethane (scenario E) resulted in a 4% cost savings.

The last three scenarios (F through H) varied the window construction. For scenario F, moving from double glass with 0.1875" air space to double glass with 0.5" air space had zero impact on the cost. Scenario G upgraded the window to double glass with 0.5" air space and low e-coating (e=0.2), increasing the price by 21%. Scenario H had the most significant cost increase at 48% due to the high cost of triple glass.


**Figure 12. Initial scenario material cost savings**

**Combination scenarios**

After the initial scenarios were run, combination scenarios were determined as defined in the Methodology section. These scenarios varied all three components at the same time, attempting to optimize cost and performance. For both of these scenarios, hardwood was chosen as the inside and outside box material. Scenario I then uses fiberglass and polyurethane foam for insulation and double paned window with an air space of 0.5”. Scenario J uses fiberglass and polystyrene for insulation and a double paned window with an air space of 0.5” and a low-e coating with e = 0.2. Results can be seen in Table 5, Table 6, Figure 13, and Figure 14.

*Thermal model*

Both scenarios I and J resulted in improved performance. Scenario I reached a peak temperature of 267 ºF, a rise time to 176 ºF of 40 minutes, and stayed above 176 ºF for 300 minutes. However, scenario J had an even greater improvement in performance. Scenario J reached a peak temperature of 330 ºF, a rise time to 176 ºF of 40 minutes, and stayed above 176 ºF for 320 minutes.

*Cost model*

Scenario I resulted in a 17% cost savings due to the substitution of inexpensive box and insulation material. However, scenario J increased the cost by 4% due to the higher price for double-glass with low e-coating. Even though scenario J also used cheaper box and insulation material, the lower cost for these materials could not offset the higher price for the glass.

*Thermal model and cost model synthesis*

The combined thermal and cost model results can be found in Table 5, Table 6, Figure 13, and Figure 14. The results on Table 6, Figure 13, and Figure 14 are normalized in reference to scenario A. On Figure 13 and Figure 14, scenario A’s performance values were each rated 4 out of 7, represented by the gray diamond, and subsequent scenarios, represented by the red polygon, were rated in reference to scenario A. Also in Figure 13 and Figure 14, improving performance and cost means minimizing cost and rise time while maximizing peak temperature and length of time with inside temperature above 176 ºF. As can be seen on these figures, scenario I demonstrates improved performance at a lower cost while scenario J also demonstrates improved performance but at a higher cost than scenario A.

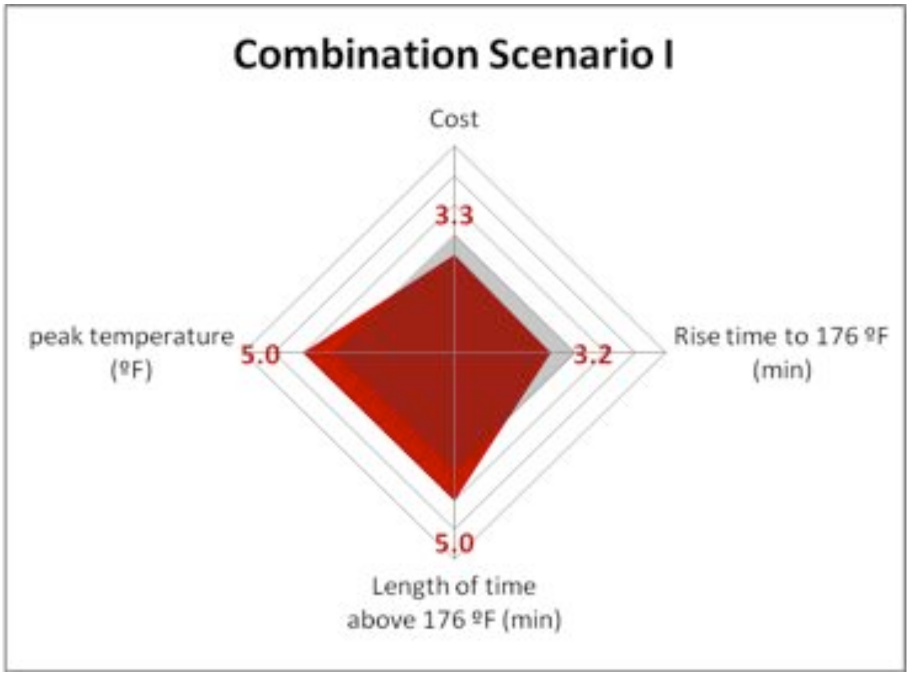



**Figure 13. Combination scenario I results in improved performance at a lower cost**

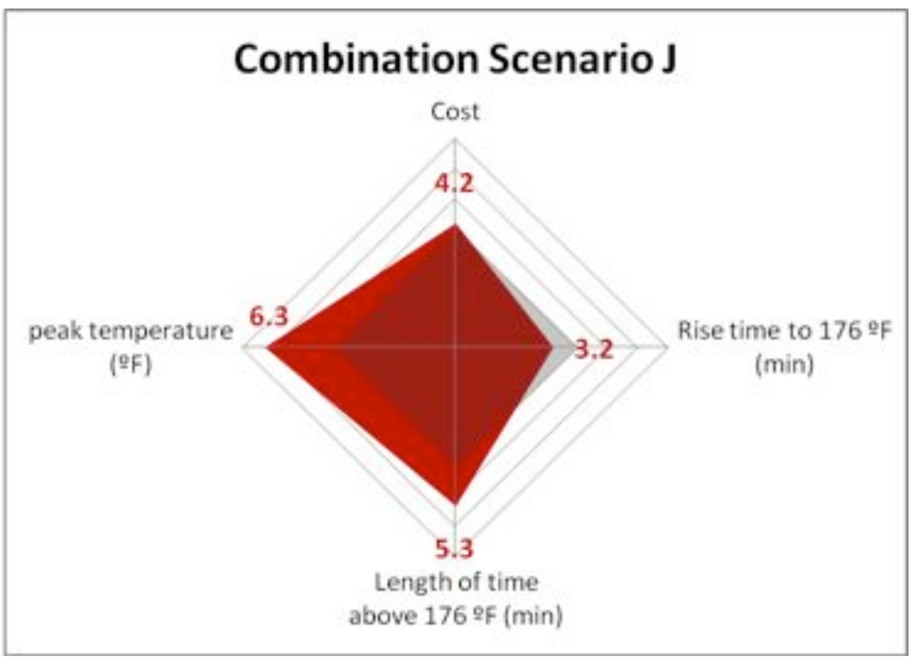



**Figure 14. Combination scenario J results in a marked improvement in performance at a higher cost**

**Table 5. Complete scenario results**

| Scenario | Cost | Rise time to 176 ºF (min) | Length of time above 176 ºF (min) | peak temperature (ºF) |
|---|---|---|---|---|
| A | 58.62 | 50 | 240 | 212.6 |
| B | 55.26 | 50 | 240 | 217.6 |
| C | 50.69 | 50 | 240 | 214.8 |
| D | 56.27 | 50 | 260 | 231.9 |
| E | 56.43 | 50 | 260 | 234.8 |
| F | 58.62 | 40 | 260 | 238.0 |
| G | 71.17 | 40 | 310 | 286.5 |
| H | 86.85 | 40 | 290 | 264.0 |
| I | 48.51 | 40 | 300 | 267.3 |
| J | 60.89 | 40 | 320 | 332.6 |

**Table 6. Scenario ratings**

| rating | Cost | Rise time to 176 ºF (min) | Length of time above 176 ºF (min) | peak temperature (ºF) |
|---|---|---|---|---|
| A | 4 | 4 | 4 | 4 |
| B | 3.8 | 4.0 | 4.0 | 4.1 |
| C | 3.5 | 4.0 | 4.0 | 4.0 |
| D | 3.8 | 4.0 | 4.3 | 4.4 |
| E | 3.9 | 4.0 | 4.3 | 4.4 |
| F | 4.0 | 3.2 | 4.3 | 4.5 |
| G | 4.9 | 3.2 | 5.2 | 5.4 |
| H | 5.9 | 3.2 | 4.8 | 5.0 |
| I | 3.3 | 3.2 | 5.0 | 5.0 |
| J | 4.2 | 3.2 | 5.3 | 6.3 |

**Prototyping**

On May 7th and 8th, 2009, stagnation tests were conducted to test the four prototypes against the performance of the commercial box cooker. On May 7th, each prototype was fitted with an acrylic window. The results from May 7th are included in Figure 15 and performance parameters are presented in Table 10.

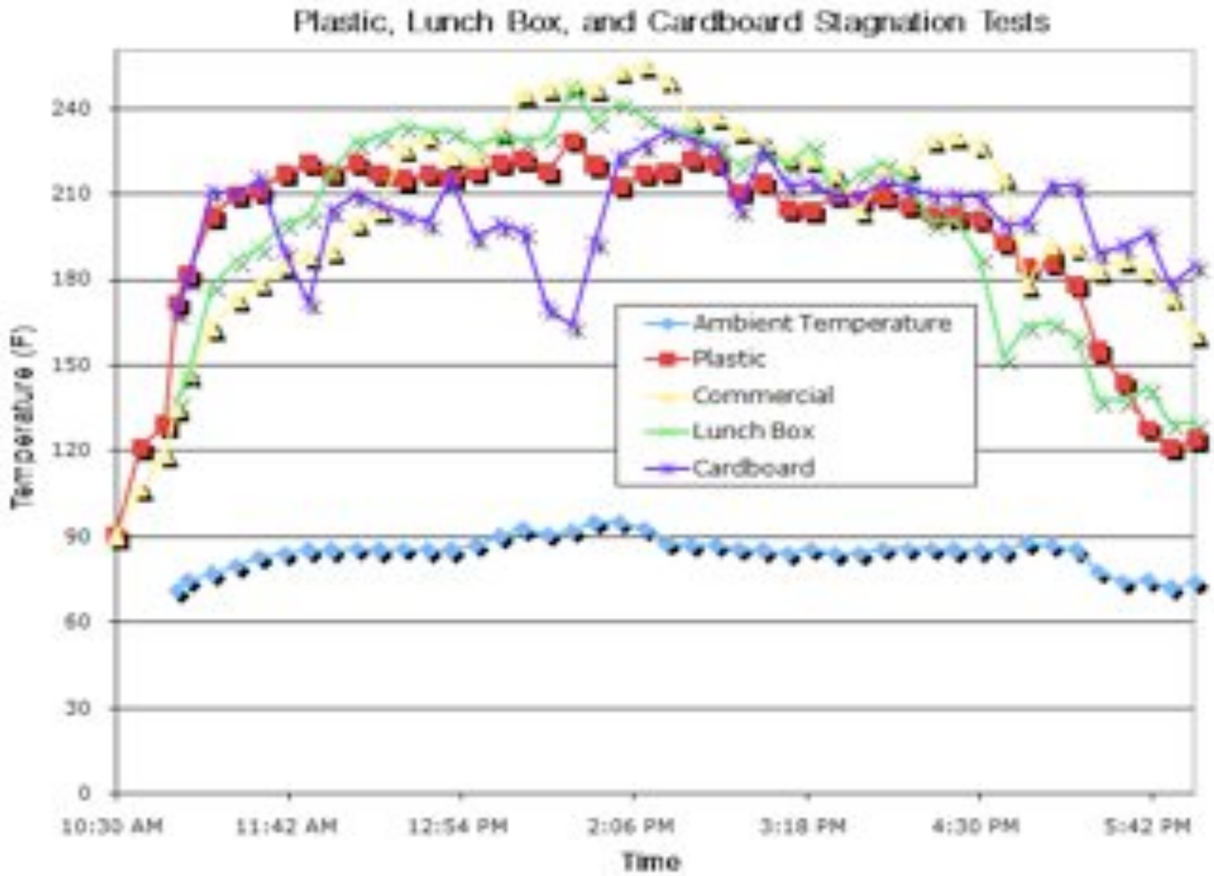



**Figure 15. May 7th Test. Plastic, cardboard, and lunchbox prototype stagnation tests graph**

| Cooker | Time to 176 ºF (min) | Time above 176 ºF (min) | Peak temperature (ºF) |
|---|---|---|---|
| Commercial Cooker | 60 | 380 | 255 |
| Plastic w/ Acrylic Cooker | 30 | 370 | 222 |
| Lunch box Cooker | 40 | 330 | 247 |
| Cardboard Cooker | 30 | 450 | 232 |

**Table 10. May 7th Test. Plastic, cardboard, and lunchbox prototype stagnation test parameters**

Cleary, the plastic, cardboard, lunch box, and commercial cooker all reached temperatures above 176°F. The commercial cooker had the highest peak temperature of 255 ºF and displayed the second longest time above 176 ºF. However, the commercial cooker required 60 minutes to reach 176 ºF, the longest rise time amongst the other cookers. The cardboard cooker reached a peak temperature of 232 °F, a value 23 ºF lower than the commercial cooker. Still, the cardboard cooker had the quickest rise time of 30 minutes and remained above 176 ºF for the longest time (450 minutes). However, the garbage bag lining inside the box began to melt after only 30 minutes and continued to deteriorate throughout the day. The plastic cooker with an acrylic window had the lowest peak temperature of 222 ºF, but reached 176 ºF twice as fast as the commercial cooker (30 minutes). Also, the plastic cooker remained above 176 ºF for 10 minutes less than the commercial cooker. Finally, the lunch box cooker performed with a peak temperature of 247 ºF, 40-minute rise time, and 330-minute time above 176 ºF.

On May 8th, the plastic and flat-packed box cookers were each fitted with a glass window. The results are included in Figure 16 and performance parameters are presented in Table 11.

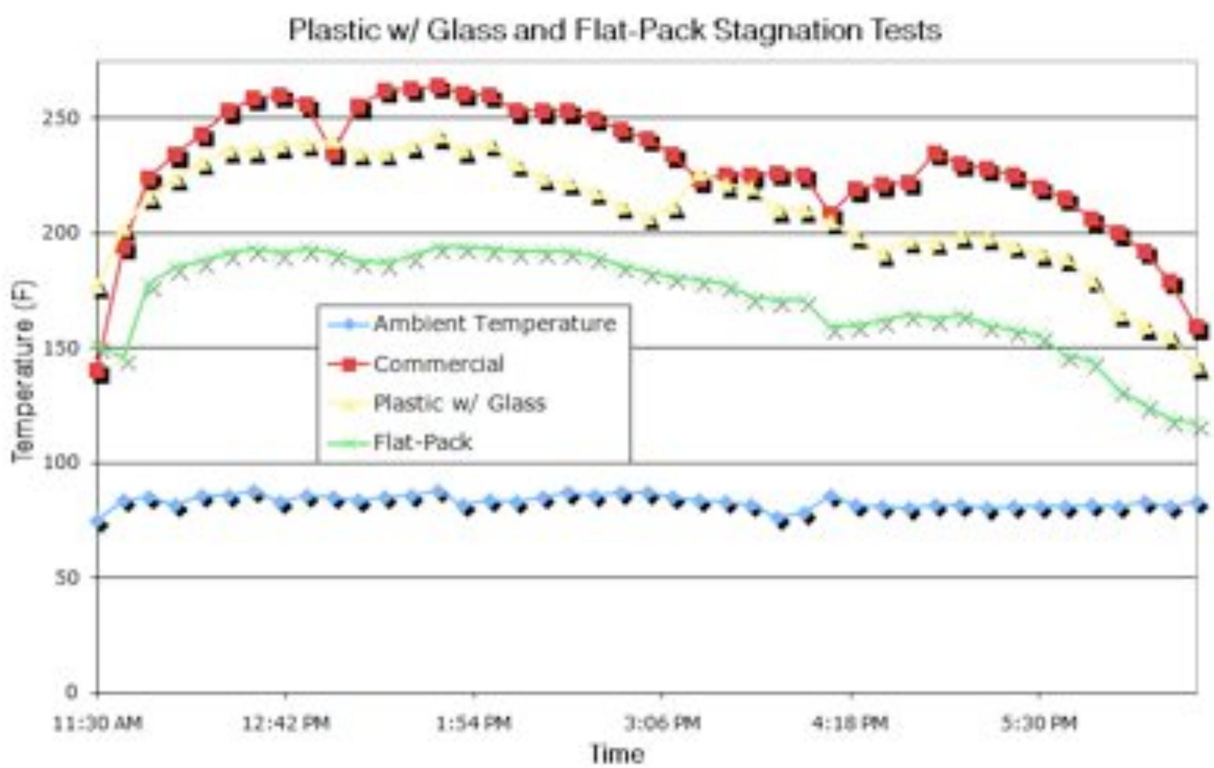


**Figure 16. May 8th Test. Plastic w/Glass and Flat-Pack prototype stagnation tests graph**

| Cooker | Time to 176 ºF (min) | Time above 176 ºF (min) | Peak temperature (ºF) |
|---|---|---|---|
| Commercial Cooker | 40 | 400 | 264 |
| Plastic w/ Glass | 30 | 380 | 242 |
| Flat-Pack Cooker | 50 | 220 | 194 |

**Table 11. May 8th Test. Plastic w/ glass and flat-pack prototype stagnation test parameters**

From the results, the commercial cooker performed slightly better than the previous day. The commercial cooker registered an improvement of 20 minutes in the rise time, 20 minutes in the length of time above 176 ºF, and 9 ºF in the peak temperature. The plastic cooker also demonstrated an improvement in performance from the previous day. The plastic cooker had a higher peak temperature of 242 ºF, a longer time above 176 ºF of 380 minutes, and a comparable rise time of 30 minutes. Despite the success of three prototypes, the flat-pack prototype did not perform similar to the commercial cooker. The peak temperature remained low at 194 ºF and the rise time (50 minutes) was nearly double that of the plastic cooker. Finally, the flat-pack cooker remained above 176 ºF for only 220 minutes.

Throughout the stagnation tests, observations were made about solar tracking and reflector positioning. The inside temperature and solar box cooker performance was dependent on orientation and solar tracking. For instance, after solar tracking the commercial solar box cooker around 1:00 P.M. on May 7th, the inside temperature increased by 23°F quickly. The relationship between max temperature versus reflector orientation and solar tracking was also readily apparent. On May 7th, the reflectors on the cardboard cooker were blown over to cover the acrylic window, accounting for the sharp drop in temperature around 1:45 P.M. Window sealing also has a large impact on solar box cooker performance. By repositioning the window seal on the cardboard cooker, thus improving air tightness, the temperature increased greatly.

**SBC stagnation and cost modeling**

The solar box cooker simulation and cost analysis has inherent uncertainties and limitations due to our assumptions and scope of our models. Major assumptions for the solar box cooker model are the basic SBC design and the data used in model calculations due to time constraints. The SBC models assume a box design based off of the Fair Fabricators SBC and is currently unable to take into account innovations in SBC design beyond material choices.

Certain generalizations were made in both the stagnation and cost model. Beyond just assuming a box design, the solar box cooker stagnation model also assumes only one reflector that is always normal to the ground. The stagnation model also currently assumes temperature and solar radiation data averaged for the month of March in the San Francisco Bay Area. The climate in this area is moderate and unlike the weather found in Gujarat, India. These assumptions were made to reasonably compare the model results to the stagnation test results from the Fair Fabricators SBC taken in March 2009 in Berkeley, CA. However, the averaged data points resulted in lower model robustness. Other sources of uncertainty in the stagnation modeling include the lack of solar transmittance factors and the assumption of 100% reflectance from the reflector.

The cost model's main sources of uncertainties lie in the cost data. The cost data used in this report were taken from retail prices from Home Depot and Berkeley Glass, both located in Berkeley, CA. These prices may not be suitable proxies to prices in India and may reflect significant retail markups over wholesaler prices. As well, materials commonly available in California may not be readily available in India and may need to be imported at significant cost. For example, one major concern is whether double paned glass and low-e coatings are readily available in Gujarat and how this will affect relative pricing. Future research on local materials and prices would help refine our cost for solar box cookers in Gujarat, India.

The current cost model focuses solely on material costs and ignores production, distribution, and shipping costs. Whether the solar box cooker is mass produced at high volumes, or built in smaller scale, low-volume job shops will have a significant impact on production costs. Location for assembly of the final product can also vary from centralized at the factory or closer to the retail outlet. This will impact the shipping costs, as SBC models that are pre-built will have significantly higher shipping costs than flat-pack designs that are more space-efficient. The weight of the final product and shipping distances will also change shipping cost estimates. These variables need to be included in the total cost of the product.

**Prototyping**

Low fidelity prototyping has an inherent discrepancy from the final product. Material selection and assemblage must change when a mass manufactured product will be made. Especially in the case of plastic molding and thin film manufacturing, the device will be inherently different when tooled and then molded, formed, or pressed. The lunchbox, plastic, and flat-pack prototypes were created with this in mind, choosing existing mass manufactured items (the plastic tubs, and the Coldpack liner) to emulate the performance of a mass manufactured final product.

The discrepancies in the material selection will be minimal. Polyurethane on the plastic prototype, corrugate plastic and thin films on the flat pack, and polyurethane on the lunch box are all reasonably accurate to the envisioned final product. In assemblage, the sealing should improve with mass manufactured precision. Therefore, it is appropriate to assume that the performance of the prototypes will only improve once mass manufactured (given no large design changes occur).

Despite uncertainties in our model assumptions and prototyping tests, the thermal and cost models and prototyping concepts provide a good foundation for future groups. The following discussion demonstrates how the thermal and cost models can inform material choices during design.

The prototyping results demonstrated each concept is a feasible low cost box cooker. Each cooker was assessed to be lacking in at least one performance metric (max temperature, structural durability, etc.). These findings provide insight into future developmental efforts needed to achieve a product ready for manufacturing.

**Modeling initial scenarios**

*Thermal model*

The results imply window construction can greatly impact solar box cooker performance, acting as the main conduit for heat loss. From the results seen above, the SBC performance varies at most by 2% depending on box material. Therefore, box shell material can be exchanged for cheaper materials as box material has negligible impact on performance. Cooker performance varies more with insulation substitutions, demonstrating around 10% improvement in peak temperature and length of time above pasteurization temperature for both insulation scenarios. Polyurethane insulation was noted to perform slightly better.

However, cooker performance varied the greatest when the window component was varied. With the different window constructions we modeled, scenarios F through H all demonstrated a decrease in rise time to pasteurization point by 20% when compared to the benchmark scenario. With only an increase in air space between the glass surfaces in a double pane construction, peak temperature increased by 12%, length of time above pasteurization point increased by 8%. When a triple paned window was run through the model, peak temperature increased 24% and length of time above pasteurization point increased by 21%. However, when a low-emissivity coating of e = 0.2 was added to the double paned window, this demonstrated the greatest improvement. When compared to scenario A's window construction, the peak temperature increased by 35% and the length of time above pasteurization point increased by 29%. Therefore, on a performance basis, a low-e double paned window is the preferred construction. However, since cost may be an issue, using less effective, but also less costly, insulation with more effective, but also more expensive, window construction may be the optimal design path.

*Cost model*

While the box material and insulation had positive cost savings from the benchmark model, any changes to the window component significantly drove up the cost (21% for double-paned low e-coating, 48% for triple-paned). Given this, it will be important to better understand user requirements for performance, their pricing sensitivity, and material availability in India. If demand is elastic and consumers will only pay a certain price for the product, it may be best to rely on cheaper and less-efficient window options.

Regardless of window construction, the final SBC solution should rely on cheaper outer box and insulation material. If the final model uses hardboard (14% cost savings) and a two-part insulation combination (fiberglass and polystyrene or polyurethane, 4% cost savings), then the final product will be 18% less expensive than scenario A.

**Modeling combination scenarios**

*Thermal model and cost model synthesis*

Since our design goal is to create a box cooker that has equal or better performance at an equivalent or lower cost, scenario I is the preferred design option. Scenario I, when compared with the benchmark scenario, has a 25% increase in peak temperature and length of time above pasteurization temperature and a 20% decrease in rise time to pasteurization temperature. Scenario J has a 33% increase in peak temperature, a 56% increase in length of time above pasteurization temperature, and a 20% decrease in rise time. However, scenario I has a decrease in cost of 17% while scenario J has an increase in cost of 4%. Therefore, although both scenarios demonstrate a marked improvement in performance, due to the higher cost resultant from scenario J, scenario I is preferred.

**Prototype Testing**

The prototype testing proved that all concepts were feasible as low cost solar box cookers. The cardboard cooker reached high temperatures (232°F) and performed well for an extended period of time (450 minutes above 176°F). However, there was material degradation noticed in only one day of testing. The internal trashbag liner melted after only 30 minutes, and the cardboard reflectors became flimsy. It became evident that cardboard and trashbags could not be used for long term cookers.

The lunch box cooker reached high temperatures (247°F) and performed well for an extended period of time (330 minutes above 176°F). Even with only one reflector, the lunch box performed well comparatively to all the cookers. The casing did not suffer from any structural damage as a result of the heat. The handle remained cool during testing allowing users to carry it home at any given moment. Proving to lack any large set backs, this concept is product ready.

The plastic cooker with acrylic windowing reached somewhat high max temperatures (222°F) and performed well for an extended period of time (330 minutes above 176°F). The plastic did not appear to suffer from any permanent structural deformations as a result of the heat. A plastic molded case seems feasible as a durable sustainable solution. The plastic cooker with glass windowing reached high max temperatures (242°F) and performed well for an extended period of time (380 minutes above 176°F). The plastic cooker with acrylic performed about 30°F below the commercial cooker, while the plastic cooker with glass performed about 20°F below the commercial cooker. This performance difference between glass and acrylic windowing was smaller than expected. Given acrylic's shatter resistance, ease or manufacturing, and lower cost, plastic may prove to be the better window alternative.

The flat-pack cooker reached low max temperatures (194°F) and did not perform well for an extended period of time (220 minutes above 176°F). There were two large fidelity issues when constructing the flat-pack cooker: the window sealing was poor, and the Coldpack could not be pumped up all the way. With these faults, the flat-pack was bottlenecked with low heat retention abilities. In order to achieve a product-ready sustainable solution, the flat pack design requires more precision and material exploration.

Further research is necessary to better understand how to spur broad adoption of a solar box cooker design without substantially changing the users' lives. This necessitates an emphasis on field research and need finding with the target population. Field research should also include research on available materials and material costs. Then once a design is produced, iterative prototyping must be implemented to ensure the ability of local technicians to create or at least maintain solar box cookers in the target area. Niche markets may also be explored to determine future target markets or help inform specialized solar box cooker designs. Once this field research has been performed and a feasible design is produced, a business plan should be implemented that focuses on user perceptions and needs. This may result in multiple public demonstrations to convince possible users of the efficacy of the design.

The models created for this project were done so to help inform future material and design choices. However, these models could be refined further. Perhaps most significantly for the thermal model is that this model is currently only capable of determining performance for a standard box cooker shape with one reflector. This model should be made to be more robust and able to take into account at least multiple reflectors and different shapes of box cookers. Also, the model does not currently take into consideration how angle of light rays may affect transmittance through the glass. For the cost model, further data gathering is required to understand local material costs, labor, overhead, and other production costs. This information would be used to build an estimate for manufacturing cost per unit. As well, additional market research and pricing analysis would help future groups gauge customers' willingness to pay, and compare that against the variable manufacturing cost.

Concept development and prototyping provided three promising solutions for bypassing the low cost barrier. First, a plastic design proved to be effective at providing structure for the cooker. Further research should be performed to understand how plastic functions as insulation. Manufacturing plans should be created for carving wooden molds and heat forming chassis. Second, the flat-pack design proved to be a durable cooker, but requires increased heat retention abilities. New methods for sealing would serve as a quick performance enhancement. Alternate insulations could greatly increase max temperature. Thin film aluminum oxide wall insulation provides a robust high resistivity insulator that won't leak over time. Argon and Xenon gas fills could be a novel approach as well. Attempts to create a sourcing partnership with Coroplast corrugated plastic and Coldpack liners would be a big step towards manufacturability. Finally, the lunch box cooker proved to be a solid concept from the stagnation test. Further testing is needed to refine sealants and determine the durability of the plastic. The initial results suggest the idea will work, but market demand needs to be determined from in-person interviews and observations.

Challenges may arise for future groups while attempting to perform field research. Perhaps one of the most difficult aspects of this project is designing a cooker with significant value since the solar box cooker market in India is already fairly saturated. Second, since solar box cooker technology has been around for a few decades, creating a cost effective solution may also prove challenging. Third, ethnography studies and feedback loops may be problematic if the project team is not located in India. An emphasis for future groups must be a trip to Gujarat to conduct this research. Finally, assessing cost performance discrepancies between a lo-fi prototype and a manufactured final product may also be a challenge.

# CONCLUSION

Over the course of this project, a number of roadblocks to further generation of solar box cookers were encountered. However, the possible benefits in spurring mass adoption of solar box cookers are large, including improvements in health and economic status. Therefore, we believe that further research should be performed to create a solar box cooker design that is cost-effective, sustainable, and fits the needs of the user. This design can result from either one of two paths, costing down the current solar box cooker design or creating an innovative new design. Both of these paths require a more broad knowledge of appropriate materials that could be utilized in creative ways in solar box cooker construction. We recommend that future steps must, most importantly, include performing on the ground field research. Information including user needs, local materials, and local manufacturing processes are necessary to inform design.

## ACKNOWLEDGEMENTS

This project was completed under the careful guidance of Dr. Ashok Gadgil and our GSI, Johanna Mathieu at UC Berkeley in the course CE 290: Design for Sustainable Communities. Their advice and supervision was critical in helping us focus our project over our four months together. We would also like to acknowledge Jonathan Slack and Howdy Goudey at the Lawrence Berkeley National Lab for assisting us in design creation and material selection. We would also like to acknowledge our other supporters in our project. This includes Tony Kingsbury from the Berkeley Sustainable Product Solutions Program and our academic colleagues including Gemma Berenguer from the Senegal SBC project and Robert Van Buskirk from the improved cook stoves project. We'd also like to thank our contacts at Solar Cooker International including Patricia Mcardle, Kevin Porter, and Tom Sponheim, as well as our India partners: Kedar Shah, and project RISHI.

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Appendix D: Explanatory Notes for SBC Cost Model

Appendix E: Interview Questions – Solar Box Cooker Users

*Appendix A. Goal Refinement*

Please note that the comments are subjective in nature, and may not be factually correct. The brainstorm happened towards the beginning of the semester when we were just embarking on the project.

A.1 Target Demographic

| | LOW INCOME | MIDDLE CLASS |
|---|---|---|
| **PROS** | • **Larger market**<br>• More visibility<br>• **Use less efficient/clean cooking options**<br>• More attracted to energy savings from use<br>• Less sensitive to time | • **More money to spend**<br>• Access to more space for device<br>• Conscious of energy benefits from use<br>• **Lower discount rate**<br>• Adoption much quicker<br>• **More innovators and early adopters**<br>• May have someone home to attend |
| **CONS** | • Cost must be lower<br>• **Higher discount rate**<br>• Lower adoption rate<br>• Whole household may be absent during the day | • More sensitive to time<br>• Compete with more efficient cooking options<br>• **Smaller market**<br>• **Smaller impact** |

| | URBAN | RURAL |
|---|---|---|
| **PROS** | • Larger Market<br>• **Easier Access/Communication for marketing, distribution, and manufacturing**<br>• **More open to innovation (more innovators and early adaptors)**<br>• Higher visibility<br>• Potentially higher income, easier access to finance | • **More space for use and easyaccessibility**<br>• More access to sunlight<br>• **Difficult to acquire resources for other cooking options**<br>• Less competition |
| **CONS** | • **More competition**<br>• **Reduced space for sun access (roof or street)**<br>• Theft could be a large concern<br>• Reduced convenience for solar box cooker use (may have to carry to roof) | • More dispersed, Lower visibility<br>• Less early adopters and innovators<br>• Less contacts (NGOs/government accessibility |

## A.2 Solar Cooking Technology

| | BOX COOKER | PARABOLIC COOKER |
|---|---|---|
| **PROS** | • Cheaper in most cases<br>• Baking capabilities<br>• Drying capabilities<br>• Variety of food<br>**• Safer**<br>**• Less tracking/attention required**<br>**• More durable/stable**<br>• Design flexibility<br>• Easy to use/Repair<br>• Thermal couple | **• High temp**<br>**• Faster/More efficient**<br>• Frying capability<br>• Aesthetically pleasing<br>• Portable<br>• Conceptually easier to use |
| **CONS** | **• Takes longer to cook**<br>**• Bulkier/Heavy**<br>• More materials<br>• No frying<br>• No use on a cloudy day | **• Unsafe – may blind or burn**<br>**• Requires more solar tracking**<br>**• Only specialized pots**<br>• Training for safety and tracking<br>• Limitations on what can cook<br>• Expensive<br>• Manufacturing more detailed<br>• No use on cloudy day<br>• No thermal couple |

| | STATIONARY | PORTABLE |
|---|---|---|
| **PROS** | • Larger design<br>• More sturdy<br>• More insulation<br>• More features to design (reflectors, thermal couples)<br>• Cooks more food at once | • Light<br>• Compact<br>• Flexible to schedule (possible take to work)<br>• Larger Market (sell multiple per family) |
| **CONS** | • Heavy<br>• Cumbersome/Difficult to move<br>• Inflexible to schedule (must be home to attend)<br>• Limits market because user must have lunch where device is located | • Design limitations<br>• Wear and tear from carrying<br>• Less food can be prepared<br>• Less Sturdy<br>• Theft |

| | ONE MEAL (LUNCH) | TWO MEALS (LUNCH + DINNER) |
|---|---|---|
| **PROS** | • Smaller<br>• Less insulation needed<br>• Less solar tracking<br>• Flexibility | • Must be efficient and maintain heat until evening<br>• More bang for buck (offset fuel costs for both lunch and dinner) |
| **CONS** | • Less bang for buck (only offset fuel costs for lunch)<br>• Difficult to change behavior for only one meal | • Solar tracking required<br>• Plan eating schedule around device<br>• May not be effective if sun is not strong or if cloudy |

## A.3 Price Point

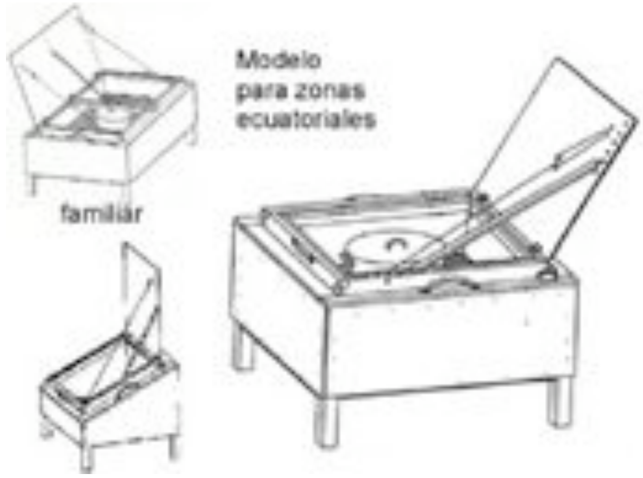
| | **HIGH PRICE** | **LOW PRICE** |
|---|---|---|
| **PROS** | • Nicer materials<br>• More durable, aesthetic<br>• Efficiency higher<br>• Status symbol<br>• More features (thermal couples, solar tracking, wheels, indicators) | • Larger Market<br>• More impact<br>• Replaceable/Spare parts available<br>• Simple design and user repairable |
| **CONS** | • Smaller market<br>• Higher expectations<br>• Repair/Service constraints<br>• Diminishing returns | • Poverty stigma<br>• Lower quality<br>• Limited material options |

*Appendix B. Competitive Benchmarking*
Please note that this competitor list is not exhaustive and there are many other local and international manufacturers of solar cookers.

## B.1 Solar Box Cookers

| **Solar Oven Society – SOS Sport** | | | |
|---|---|---|---|
|   | | | |
| **Target Market** | Mainly for recreational cooks in the USA but cookers have been sent to developing countries | **Geographic Coverage** | Available only in the US, but can be bought for projects in developing countries |
| **Distribution Channels** | Pre-built: SOS | **Affiliated w/ NGO, gov't** | Sponsored by Persons Helping People, a non-profit corporation established in Minnesota. |
| | | | |
| **Materials List** | Recycled plastic, insulation | **Pricing** | $99 |
| **Product Features** | • Temperatures reached: 94-142 degrees C<br>• Weighs 10 lbs<br>• Comes with 2 pots with lids, a thermometer, an instruction manual and a WAI (water pasteurization indicator) | | |
| **Strengths** | | **Weaknesses** | |
| • Light - portable<br>• Can adopt two inclinations | | • Expensive<br>• Small<br>• For recreational use only | |
| **Other** | | | |
| **Website** | http://www.solarovens.org/index.html | | |

<table>
<tr><th colspan="4">Sun Ovens International – Global Sun Oven</th></tr>
<tr><td colspan="4"> </td></tr>
<tr><td>Target Market</td><td>Families of 6-8 in developing countries</td><td>Geographic Coverage</td><td>125+ countries; Produced in US, Afghanistan, DR, Ghana, Haiti, Nepal, North Korea, South Africa.</td></tr>
<tr><td>Distribution Channels</td><td>1. Country programs w/local mftg<br>2. Independent dealers / distributors.<br>3. NGO / PVO organizations</td><td>Affiliated w/ NGO, gov't</td><td>Yes, programs with NGO / PVOs. Differs by country but many programs with Rotary International</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Materials List</td><td>External case: resistant ABS plastic;<br>Frame: wooden; Interior box: aluminum w/non-toxic paint;<br>Insulation: rock wool;<br>Window/cover: hardened glass<br>Reflectors: anodized aluminum</td><td>Pricing</td><td>Retails for $289 in US, plus postage. Partners with microfinance organizations to allow ovens to be paid in installments. Local assembly option</td></tr>
<tr><td>Product Features</td><td colspan="3">• Cooking temperatures of 182° Celsius, though field tests show max at 160; built-in thermometer<br>• Weighs 21 pounds (9.5kg)<br>• Will last more than 20 years<br>• No ongoing maintenance other than cleaning<br>• Claims to have cooking temperatures significantly higher than other solar devices<br>• “High quality” material<br>• Well-insulated, claims to keep food cooked in afternoon warm into the evening</td></tr>
<tr><td colspan="2">Strengths</td><td colspan="2">Weaknesses</td></tr>
<tr><td colspan="2">• SUN OVENS has developed local assembly plant system, including training, tools, instructional material, support<br>• Time required to cook food is comparable to wood/charcoal fire due to high cooking temperatures</td><td colspan="2">• Expensive<br>• “Assembly” plant still requires purchase of unassembled kits<br>• Manufacturer recommends re-orienting cooker every 30 minutes</td></tr>
<tr><td>Other</td><td colspan="3">Also offer a “Villager Sun Oven”</td></tr>
<tr><td>Website</td><td colspan="3">https://www.sunoven.com/international/global-sun-oven.php</td></tr>
</table>

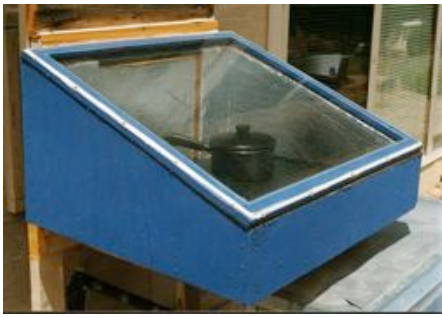
| **ULOG – Ulog Standard Model** | | | |
|---|---|---|---|
|   | | | |
| **Target Market** | Both equatorial and nonequatorial users | **Geographic Coverage** | Based in Switzerland and Germany but develops and promotes SBCs in Europe, India and Africa. |
| **Distribution Channels** | Self-built: plans available on website for free<br>Offers cooking maps | **Affiliated w/ NGO, gov't** | The ULOG group is a "loosely organized" NGO. Its allied with Solare Bruecke (Scheffler cookers). |
| | | | |
| **Materials List** | Glass, wood, black paint, bakelised plywood, aluminum/tin foil, galvanized steel hinges, steel nails, mineral wool mats, | **Pricing** | In Europe possible to get the cooker for 199 or 299 Euros depending on the area. |
| **Product Features** | • Standard:<br>  • Dimensions 67x67x50 cm, maximum pot height 19cm<br>  • Weight 9 kg<br>• Family size<br>  • Dimensions 120x67x50 cm, maximum pot height 19cm<br>  • Weight 13 kg | | |
| **Strengths** | | **Weaknesses** | |
| • Main material is wood so can be resilient in bad/windy weather<br>• Easily found materials | | • can't find a ULOG website<br>• Expensive | |
| **Other** | Having problems finding ULOG, it might be defunct now | | |
| **Website** | http://www.med.uni-magdeburg.de/~maercker/SolCook/SolCook.html | | |

| ULOG – Ulog Light Model | | | |
|---|---|---|---|
|   | | | |
| **Target Market** | Both equatorial and nonequatorial users | **Geographic Coverage** | Based in Switzerland and Germany but develops and promotes SBCs in Europe, India and Africa. |
| **Distribution Channels** | Self-built: plans available on website for free<br>Offers cooking maps | **Affiliated w/ NGO, gov't** | The ULOG group is a "loosely organized" NGO. Its allied with Solare Bruecke (Scheffler cookers). |
| | | | |
| **Materials List** | Light wood, wool, recycled printing aluminum sheets, black paint, nylon fabric, glass, plastic sheet | **Pricing** | In Europe possible to get the cooker disassembled in kit form for 183 or 193 euros |
| **Product Features** | • Standard:<br>  • Dimensions 50x52x45 cm<br>  • Weight 5 kg<br>• Reaches temperatures higher than 130º C | | |
| **Strengths** | | **Weaknesses** | |
| • Portable and very light<br>• Cooks for three people<br>• Resistant materials for outside cooking (obviously)<br>• Readily dismountable | | • Designed for "countryside days"<br>• Expensive<br>• Doesn't include thermometer or pot | |
| **Other** | Having problems finding ULOG, it might be defunct now | | |
| **Website** | http://www.med.uni-magdeburg.de/~maercker/SolCook/SolCook.html | | |

| Lazola | | | |
|---|---|---|---|
|   | | | |
| **Target Market** | All developing nations families | **Geographic Coverage** | South Africa, expanding |
| **Distribution Channels** | Through Lazola-Initiative? | **Affiliated w/ NGO, gov't** | Lazola-Initiative |
| | | | |
| **Materials List** | galvanized sheet metal reflector, anodized sheet aluminium pot, wooden frame | **Pricing** | 65 EUR for materials |
| **Product Features** | • Solar box cooker made from prefabricated lightweight metal sheets<br>• Ongoing project so each iteration comes with good insight about implementation | | |
| **Strengths** | | **Weaknesses** | |
| • Designed for local serial production by hand<br>• Local production could create value<br>• Comes with instructional film | | • Sheet metal is prefabricated - must be cut with special tools<br>• Manufacturing process is complex | |
| **Other** | | | |
| **Website** | [http://www.lazola.de/english.html](http://www.lazola.de/english.html) | | |

<table>
<tr><th colspan="4">SunOK</th></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Target Market</td><td>Europe</td><td>Geographic Coverage</td><td>Available in Africa (Cabo Verde, South-Africa, Senegal) and Europe (Denmark, France, Spain)</td></tr>
<tr><td>Distribution Channels</td><td>Manufactured in industrial scale in Europe</td><td>Affiliated w/ NGO, gov’t</td><td>No</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Materials List</td><td>Recycled plastic, aluminum reflectors, glass</td><td>Pricing</td><td>Not listed</td></tr>
<tr><td>Product Features</td><td colspan="3">• Dimensions 59x55x29 cm<br>• Weight: 13 kg (including pots and handbook)<br>• Includes a handbook and recipe book<br>• At 40 degrees north latitude, reaches around 150 degrees C, near the equator reaches around 200 degrees C</td></tr>
<tr><td colspan="2">Strengths</td><td colspan="2">Weaknesses</td></tr>
<tr><td colspan="2">• Resilient materials<br>• Reaches high temperatures</td><td colspan="2">• Heavy</td></tr>
<tr><td>Other</td><td colspan="3"></td></tr>
<tr><td>Website</td><td colspan="3">www.sunok.eu (link doesn’t work)</td></tr>
</table>

| **Nevehorno** | | | |
|---|---|---|---|
|  | | | |
| **Target Market** | Not clear, but given price point and sophistication for affluent | **Geographic Coverage** | Not clear |
| **Distribution Channels** | Not there yet | **Affiliated w/ NGO, gov't** | Does not appear to have any affiliations |
| | | | |
| **Materials List** | Fibreglass, polyurethane, galvanised iron, aluminium and tempered glass | **Pricing** | 850 Euros |
| **Product Features** | • Developed to cook both solid and liquid food products and as a passive solar fridge. | | |
| **Strengths** | | **Weaknesses** | |
| • Able to use many energy sources: solar, electricity, wood, charcoal, biomass, etc.<br>• Can maintain low temperatures for up to 12 hours without any energy<br>• Digital system which advises how much energy is needed should the solar energy be insufficient and allows an alternative to be used<br>• The oven can be used at night time or in covered areas using 500 w of energy which is about a quarter of a similar sized conventional oven<br>• The temperature is controlled electrical so that no food is burnt<br>• The nevehorno has a capacity of 60 litres and can cook or bake 12 pounds of meat/chicken/fish in 45 minutes | | • Patent Pending - may not exist yet<br>• Price | |
| **Other** | | | |
| **Website** | No official site http://www.terra.org/html/s/sol/cocina/directorio/fichaen.php?id=66 | | |

| Kerr-Cole – Through the Wall SBC | | | |
|---|---|---|---|
|    | | | |
| **Target Market** | Homeowners, primarily in developed countries | **Geographic Coverage** | Not available |
| **Distribution Channels** | DIY guidelines available online | **Affiliated w/ NGO, gov't** | No |
| | | | |
| **Materials List** | Exterior: wood<br>Interior: insulating material, cardboard, metallic sheet/paper<br>Window: double-paned glass<br>Bottom: metallic and black sheet | **Pricing** | Flexible material selection to allow for local availability and/or home capability |
| **Product Features** | • Can reach 120-140° Celsius on a sunny day<br>• Product can be purchased or DIY instructions available online | | |
| **Strengths** | | **Weaknesses** | |
| • Can be operated from inside home like conventional oven | | • Permanent structure<br>• Cannot be re-oriented to face the sun | |
| **Other** | Website has very good information on how to buy appropriate materials and construct a SBC. | | |
| **Website** | http://www.solarcooking.org/bkerr/DoItYouself.htm | | |

| Sun Spot Solar & Heating - Sunspot | | | |
|---|---|---|---|
|  | | | |
| **Target Market** | "New to solar and curious" | **Geographic Coverage** | USA |
| **Distribution Channels** | http://www.safetycentral.com | **Affiliated w/ NGO, gov't** | nope |
| | | | |
| **Materials List** | cardboard aluminum sheets plastic sheets | **Pricing** | $49 USD |
| **Product Features** | • Small box oven sold as a survival kit<br>• Reflective surfaces concentrate the radiation into a central chamber<br>• Most often used as an educational tool, it makes a good start to solar cooking or as an addition to existing solar cookers | | |
| **Strengths** | | **Weaknesses** | |
| • Can reach above 150 ºC (300 ºF) Can reach 175 ºC (350 ºF) when cooking small amounts of food<br>• oven folds into a box and comes with a manual | | • This oven has a small capacity and it suitable for cooking small quantities of food for one person<br>• Must prop against something | |
| **Other** | | | |
| **Website** | http://www.safetycentral.com | | |

| Sunstove | | | |
|---|---|---|---|
|   | | | |
| **Target Market** | Small cooker designed for large production anywhere | **Geographic Coverage** | Intended for anywhere |
| **Distribution Channels** | None Mentioned | **Affiliated w/ NGO, gov't** | None |
| | | | |
| **Materials List** | Aluminum, glass fiber insulation, acrylic plastic window | **Pricing** | $20 USD |
| **Product Features** | • Cooks for 6 people, 4-5 liters of rice, 1-2 liters of vegetables or meat<br>• 55.1 X 69 X 35 cm<br>• 8 lbs | | |
| **Strengths** | | **Weaknesses** | |
| • Food temperature can reach 212 °F<br>• Can be made from diverse materials to allow local production in every country<br>• Case is made from molding plastic but can be made from wood or cardboard | | • No consideration for local customs or preferences<br>• Plastic glass may lose radiation | |
| **Other** | | | |
| **Website** | http://www.sungravity.com/sunstove.html | | |

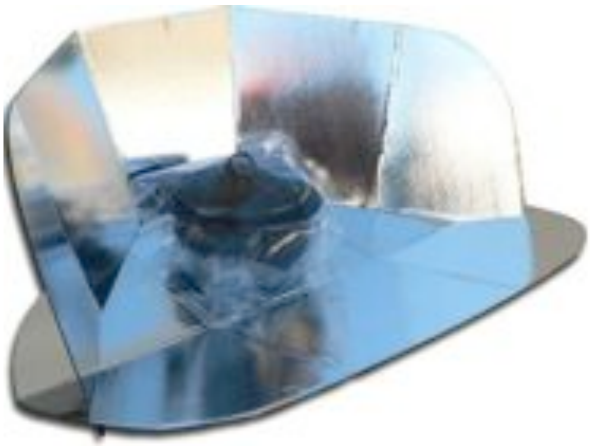
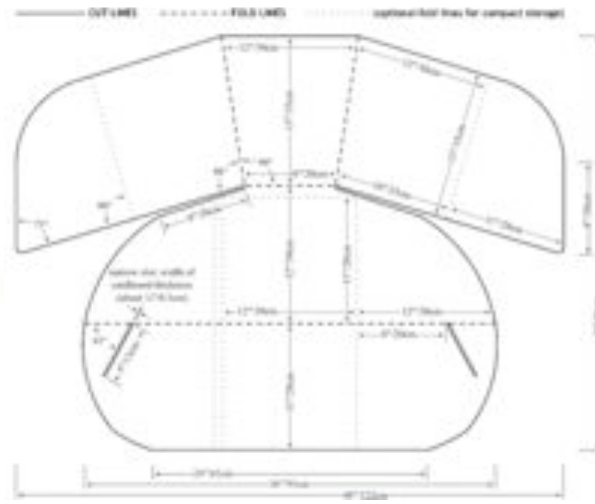
**Synopsis REM5**

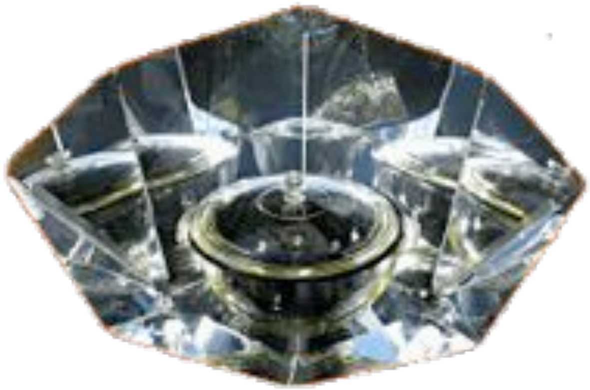

| | | | |
|---|---|---|---|
| **Target Market** | Designed for cooperation projects in developing countries | **Geographic Coverage** | South Africa |
| **Distribution Channels** | None Mentioned | **Affiliated w/ NGO, gov't** | None |
| | | | |
| **Materials List** | Polycarbonate, aluminum, glass | **Pricing** | None Mentioned |
| **Product Features** | • Designed for accumulation and concentration of sunlight<br>• 88 X 101 X 96 cm<br>• 3 external reflectors | | |
| **Strengths** | | **Weaknesses** | |
| • Maximum temperature is 147 °C in frying oil after 130 minutes | | • Fabrication requires patience and availability of tools | |
| **Other** | | | |
| **Website** | http://www.terra.org/html/s/sol/cocina/directorio/fichaen.php?id=17 | | |

| Nelpa | | | |
|---|---|---|---|
|  | | | |
| **Target Market** | Designed to provide heat on bottom of oven | **Geographic Coverage** | None Mentioned |
| **Distribution Channels** | None Mentioned | **Affiliated w/ NGO, gov't** | None |
| | | | |
| **Materials List** | Wood frame, glass window, aluminum reflectors | **Pricing** | €25 |
| **Product Features** | • Combination unit of box oven and parabolic cooker<br>• Movable parabolic unit focuses radiation on bottom of oven<br>• Box has glazed window to retain heat | | |
| **Strengths** | | **Weaknesses** | |
| • Maximum temperature is 140 °C<br>• Food remains accessible for seasoning and tasting | | • Requires frequent adjustment to follow the sun | |
| **Other** | | | |
| **Website** | http://solarcooking.org/plans/nelpa.htm | | |

| **Pil Kaar** | | | |
|---|---|---|---|
|  | | | |
| **Target Market** | Commercially made cooker sold around the world | **Geographic Coverage** | Eastern regions of Chad |
| **Distribution Channels** | None Mentioned | **Affiliated w/ NGO, gov't** | French Polar Institute (IPEV) |
| | | | |
| **Materials List** | Hemp insulation, glass window, aluminum reflectors, acrylic mirror | **Pricing** | €25 |
| **Product Features** | • Includes one internal and external reflector<br>• 44 X 44.5 X 30 cm | | |
| **Strengths** | | **Weaknesses** | |
| • Maximum temperature is 170 °C<br>• Reaches 80 ºC without reflector | | • 10 kg in weight | |
| **Other** | http://www.terra.org/html/s/sol/cocina/directorio/fichaen.php?id=72 | | |
| **Website** | http://solarcooking.wikia.com/wiki/Pil_Kaar | | |

B.2 Parabolic Solar Cookers

| **Solar Cookers International - CooKit** | | | |
|---|---|---|---|
|  | |  | |
| **Value Proposition** | Addresses fuelwood scarcities; Improves health; Enhances household and women's economic status | | |
| **Target Market** | Refugee camps in Africa | **Geographic Coverage** | Independently produced in 25 countries. Local production setup in Nairobi, Kenya |
| **Distribution Channels** | Pre-built: SCI<br>Self-built: plans available on website for free | **Affiliated w/ NGO, gov't** | SCI is a volunteer group of engineers and solar cooks. Discounts offered to NGOs. Some partners include Jewish World Watch, Dutch foundation KoZon |
| | | | |
| **Materials List** | Cardboard, aluminum foil, dark-colored pot, high-temperature plastic bag | **Pricing** | Wholesale cost of $3-7 USD. Pre-built Cookit is $15-$25 depending on order qty |
| **Product Features** | • Start with large piece of cardboard (3' x 4'). Cut and fold as indicated in blueprints. Glue aluminum foil on inside surfaces. Fold up sides and fit corners into indicated slots.<br>• Ready to cook! Put food in dark-colored pot. Put plot inside plastic bag. Close open end of bag and place pot & bag into center of cooker | | |
| **Strengths** | | **Weaknesses** | |
| • Weighs half a kilogram<br>• Folds to size of book for easy transport<br>• Can make meals for 5-6 people<br>• Low cost, from readily available materials<br>• Very inexpensive | | • Last for 2 years (pre-built CooKit)<br>• Cardboard does not have long-life<br>• May not be as effective as metal solar cookers | |
| **Other** | Can build own CooKit (using free plans) or order pre-built from SCI | | |
| **Website** | http://solarcooking.wikia.com/wiki/CooKit | | |

<table>
<tr><th colspan="4">Olla Solar – Hot Pot</th></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Target Market</td><td>Families who could benefit from safety, and affordability</td><td>Geographic Coverage</td><td>Oaxaca, Mexico but expanding</td></tr>
<tr><td>Distribution Channels</td><td>Works through private entities, governments and local NGOs</td><td>Affiliated w/ NGO, gov't</td><td>http://www.she-inc.org/partners.php</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Materials List</td><td>Pot – steel and tempered glass; reflector – either aluminum foil with cardboard or anodized aluminum with hinges</td><td>Pricing</td><td>$100 for pot + $25 shipping</td></tr>
<tr><td>Product Features</td><td colspan="3">• Collapsible metal reflector that surrounds a big Pyrex bowl with lid<br>• There is a 3cm gap between the glass container and the black pot which creates a glasshouse effect allowing cooking.</td></tr>
<tr><td colspan="2">Strengths</td><td colspan="2">Weaknesses</td></tr>
<tr><td colspan="2">• Portable<br>• Minimal material<br>• Cooking takes only twice as long as open frame<br>• Provide solar cookbooks<br>• attractive</td><td colspan="2">• Pot might be hard to manufacture locally<br>• Could get blown away<br>• Only one pot</td></tr>
<tr><td>Other</td><td colspan="3"></td></tr>
<tr><td>Website</td><td colspan="3">http://www.she-inc.org/</td></tr>
</table>

B.3 Community Solar Cookers

| **Sun Ovens International – Villager Sun Oven** | | | |
|---|---|---|---|
|   | | | |
| **Target Market** | Villages in developing countries (1200 meals/day) | **Geographic Coverage** | Currently 51 micro-sun-bakeries in 6 countries |
| **Distribution Channels** | Direct from Sun Ovens International | **Affiliated w/ NGO, gov't** | Rotary clubs |
| | | | |
| **Materials List** | Base made of rigid plastic<br>Reflectors are aluminum | **Pricing** | In EU, price starts at $9500 and increases depending on accessories; Primarily funded by Rotary clubs around the world |
| **Product Features** | • Cooking temperatures of 500° F/ 260° C<br>• Sun-Bakeries micro-enterprise; 150-piece Sun-Bakery package that includes baking pans, rolling pins, etc<br>• Easy track system adjusts to follow sun<br>• Propane back-up system so can be operated 24/7<br>• Trailer mounted<br>• Fast setup (10 minutes) and take-down (5 minutes) | | |
| **Strengths** | | **Weaknesses** | |
| • Biggest commercial solar cooker on market<br>• Rotation system to orient solar cooker to sun<br>• Propane backup so can be used during bad/rainy weather | | • Not appropriate for our target segment (unless as business)<br>• Very expensive! | |
| **Other** | Bakery business model: https://www.sunoven.com/international/sun-bakeries.php | | |
| **Website** | https://www.sunoven.com/international/villager-sun-ovens.php | | |

*Appendix C. Explanatory Notes for SBC Thermal Model*

C.1 How to use SBC model

*Inputs*

This first run through simulation of the performance of a solar box cooker requires the user to input solar box cooker (SBC) dimensions, orientation and solar tracking, and basic materials. The orientations of the SBC are based off of the assumption that due south is 0º, due east is 90º, and due west is -90º. Wall construction needs to be inputted for all walls part of the cooking portion of the SBC, this includes not only the surrounding four walls but the bottom and the window construction as well. Materials need to be inputted going from inside to outside. These materials can be chosen from a drop down list which refers to a materials list in the 'Material Properties' tab.

**Example inputs:**

**Table C.1 Example SBC geometry inputs**

| SBC Geometry | |
|---|---|
| height of reflectors, h (in) | 22 |
| width of outside box, wo (in) | 22 |
| length of outside box, Lo (in) | 22 |
| width of inside box, wi (in) | 16 |
| length of inside box, Li (in) | 16 |
| depth of box (in) | 4 |

**Table C.2 Example solar tracking inputs**

| Solar heat gain | | |
|---|---|---|
| **Orientations of SBC (pos - E, neg - W)** | | **Time** |
| Initial | 38.8 | 10:00 AM |
| 2nd | -35.8 | 1:50 PM |
| 3rd | | |

**Table C.3 Example wall construction inputs**

| Wall 1 | | Top | |
|---|---|---|---|
| **Material** | **thick. (in)** | **Material** | **Thick. (in)** |
| Hardboard - high density - 1/8" x 4' x 8' | 0.125 | Double glass - 0.5" air space | 0.5 |
| Fiberglass - 1" thick | 1 | | |
| Spray Applied - Polyurethane foam 2" | 2 | | |
| Hardboard - high density - 1/8" x 4' x 8' | 0.125 | | |

After these parameters are inputted the user will have to manually change the orientation (if solar tracking is performed) in the 'Solar Heat Gain' tab. This means that if the above example orientations are used in the model then the user needs to go to the 'Solar Heat Gain' tab, go to the time of the next orientation change (in this case 1:50 PM) and change the formula in the reflector surface azimuth to reference the next orientation angle and then copy this down in the following rows until the next (if any) orientation change. Please see following table.

**Table C.4 Manually change any orientation changes in 'Solar Heat Gain'**

| hour | azm | alt | reflector surface azimuth | profile angle |
|---|---|---|---|---|
| 1:30 PM | -29.8 | 40.5 | -68.6 | 17.3 |
| 1:40 PM | -32.8 | 39.5 | -71.6 | 14.6 |
| 1:50 PM | -35.8 | 38.6 | 0.0 | 38.6 |
| 2:00 PM | -38.8 | 37.6 | -3.0 | 37.5 |
| 2:10 PM | -41.3 | 36.2 | -5.5 | 36.0 |

To see results, go to the 'Results' tab and the inside temperature will be tabulated and graphed from 10:00 AM until 4:00 PM (see following figure). Currently, there is also a column that checks whether the inside temperature is above the pasteurization temperature, 176 °F. The efficiency parameters that we used in our study are peak temperature, rise time to 176 °F and length of time where inside temperature is above 176 °F. These are found in a table to the right of the results, but only peak temperature is automatically determined. For the other two you must input the times to the right of that box under start time and end time above 176 °F.

**Figure C.1 Example SBC model results graph**

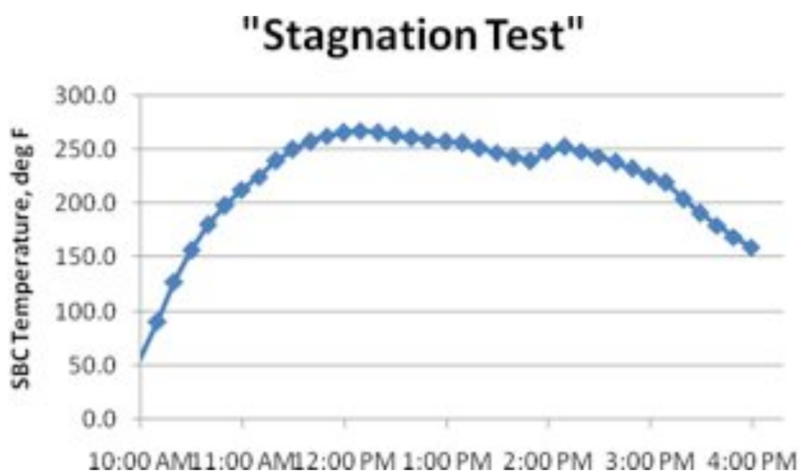



**Table C.5 Example efficiency parameters and inputs**

| Efficiency Parameters | | | | | |
|---|---|---|---|---|---|
| peak temperature (°F) | 267.3 | | | | |
| Rise time to 176 °F (min) | 40 | | | | |
| Length of time above 176 °F (min) | 300 | start time above 176 | 10:40 AM | end time above 176 | 3:40 PM |

C.2 SBC model explanatory notes

The SBC model basically solves the energy ODE equation:

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{acc}$$

Where $\dot{Q}_{in}$ is the heat gain term, $\dot{Q}_{out}$ is the heat loss term, and $\dot{Q}_{acc}$ is the heat accumulation within the SBC term. The determination of each term and the assumptions within each determination will be discussed in the following sections.

*C.2.1 Heat gain*
The heat gain term is calculated as

$$\dot{Q}_{in} = \left(A_{refl} + A_{window}\right) * S * \sin(\beta)$$

Where S is the solar radiance [W/m$^2$], β is altitude [º] and $A_{refl}$ and $A_{window}$ [m$^2$] represent the amount of radiance (direct and reflected from the reflector) the window of the SBC is exposed to. The solar radiance is multiplied by the sine of the altitude to take into account the amount of radiation that falls normal to the window.

C.2.1.1 Data sources
The solar radiation data can be found under the 'Radiation' tab. This data is taken from the National Renewable Energy Laboratory solar radiation data for the San Francisco International Airport (manual and full data set can be found in the electronic SBC team binder). Currently the model is using an averaged solar radiation data for the month of March as that is when we performed our stagnation test on Professor Ashok Gadgil's SBC. The azimuth and altitude data are taken for Berkeley's latitude (38ºN) and the month of March and are taken from ARCH 140's SHADE program.

C.2.1.2 Calculations
To determine the amount of radiance the SBC window is exposed to, both direct and indirect radiation need to be considered. For direct radiation, only the area of the window and the altitude need to be considered to take into account the amount of solar rays falls normal to the window, since we are assuming the window to be horizontal, which is represented by the term $A_{window}$. However, to determine indirect radiation the amount of light reflected from the reflectors that falls onto the window needs to be calculated. To calculate this, first the profile angle (Ω) needs to be determined using azimuth (α), altitude (β), and reflector solar surface azimuth (γ). Azimuth is the degrees west (negative) or east (positive) the sun is from due south. Solar altitude is the angle between the horizontal plane and a line from a point to the sun. Reflector solar surface azimuth is the angle between a line normal to the reflector and the sun, and can be determined by subtracting the orientation of the SBC from the solar azimuth. Please see following figure for graphical demonstration of above angles, where Q is the sun location and VYX is the plane of the reflector surface.

From these above angles, the profile angle can be calculated using the following equation

$$\Omega = TAN^{-1}(TAN(\beta)*COS(|\gamma|)$$

Then, using this profile angle, how much light from the reflector that lands on the window can be determined and is represented by the term $A_{refl}$. We currently assume 100% reflectance from the reflector.

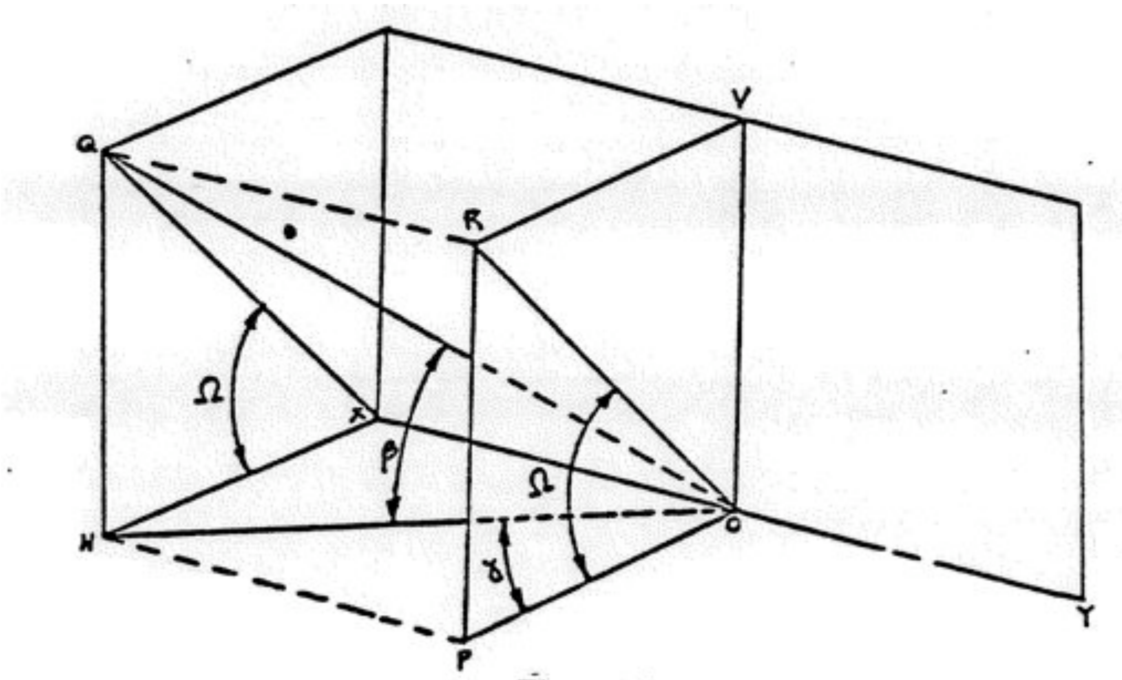



**Figure C.2 Solar geometry figure (ARCH 140 Reading 19, 2009)**

### *C.2.2 Heat loss*

The heat loss term is calculated as

$$\dot{Q}_{out} = UA_{eff} * (T_{inside} - T_{outside})$$

Where $UA_{eff}$ is the overall UA term for the surrounding walls and the window and $T_{inside}$ and $T_{outside}$ are the temperatures inside and outside of the box.

$UA_{eff}$ is determined by calculating the amount of heat loss per time (U-value) by conduction and convection from the walls and the window and multiplying each by their respective areas. The U-value is a property readily given by most window manufacturers. However, to calculate the U-value for the walls, the R-value, or the resistance to heat loss value, must be determined for each material (sheet metal, insulation, etc.). The R-values can be found in the 'Material Properties' tab. Then the reciprocal of the total R value for each wall will be the U-value. Air film coefficients were assumed to be 0.5 for both inside and outside. $UA_{eff}$ is then the sum of all the UA terms. For a more detailed discussion of $UA_{eff}$, please refer to ARCH 140 Lecture 10, which is labeled building envelope heat loss in the SBC model folder in the SBC team electronic binder.

$T_{inside}$ is determined from the previous step's heat gain coefficient and will be discussed further in the following section. $T_{outside}$ is taken from the average temperature in March in San Francisco from 1990-2006 which can be seen in the tab 'Outside Temperature'. However, since the outside temperature is only taken for each hour, the temperature is linear interpolated for each ten minutes between the hour marks.

*C.2.3 Heat accumulation*

The heat accumulation term is calculated to be:

$$\dot{Q}_{acc} = TM * \frac{dT}{dt}$$

where TM stands for the thermal mass of the air inside the box as well as half of the box and dT/dt stands for the change in temperature with time. The thermal mass of each component is calculated to be the volumetric heat capacity (VHC) of the material times the volume of the material.

This problem then boils down to a simple ODE equation solution which can be generalized to determine the inside temperature to be:

$T_{i+1} = \; A_{i+1} - B_{i+1} * e^{-kt}$

where

$$A_{i+1} = (T_{outside,i} + UA_{eff} * Q_{in,i})/UA_{eff}$$

$$B_{i+1} = T_i - A_{i+1}$$

$$k = 1/TM$$

And t stands for time.

**References**


ARCH 140 Energy and Environmental Management. Reading 19: Solar geometry variables. College of Environmental Design, UC Berkeley, Spring 2009.

ARCH 140 Energy and Environmental Management. Lecture 10: Whole building heat loss. College of Environmental Design, UC Berkeley, Spring 2009.

*Appendix D. Explanatory notes for SBC Cost Model*

## D.1 Cost Model

*Solar Box Cooker Dimensions*

For the purposes of the solar box cooker cost model, we aggregated the full component list into five major categories: outer box material, insulation, window, reflector, and internal structural material. Components that are not included in these categories include screws, nails, hinges, sealants, paint/coatings, and castors. These components were omitted from the model because their individual prices were considered negligible as compared to the primary components.

To determine the relative amount needed for each component, we measured the dimensions for the Fair Fabricators solar box cooker (scenario A). After measuring the dimensions, we calculated the square /cubic feet required for each of the materials. The results are in Table D.1.

**Table D.1 SBC dimensions and required quantity**

| | Dimensions for Standard SBC (Fair Fabricators) | Required Qty | |
|---|---|---|---|
| Outer | External: (4) 4" x 22"; (4) 2" x 22"; (2) 22" x 22"<br>Internal: (4) 4" x 16"; (1) 16" x 16"; (1) 22" x 22" | 17.31 | sq ft |
| Insulation | (4) 4" x 20" x 2"; (4) 2" x 20" x 2"; (1) 16" x 16" x 2" | 0.852 | cu ft |
| Window | (1) 22" x 22" | 3.36 | sq ft |
| Reflector | (1) 16" x 16" | 1.78 | sq ft |
| Structural | (4) 4" x 20" x 2" | 1.67 | ft of 2' x 2' |

Note that only the outer, insulation, and window components will be changed in the cost and thermal model. The reflector and structural components are included as a substantial part of the overall cost but will remain static throughout the simulation.

*Material List*

Material prices were obtained by visiting retail outlets in the San Francisco Bay area, more specifically Home Depot and Berkeley Glass. These costs reflect the retailer markup, which can be quite substantial for some products. Wholesaler prices and Indian prices were not obtained at this time.

For each material, we recorded the unit of measure (e.g. sq ft) and prices. We then calculated the unit price by dividing price by UOM. These numbers were used to compare relative cost performance in similar categories.

*BOM*

Using the 10 scenarios described in the paper as a guide, we then created a detailed BOM for each of the five primary components. See Table D.2. for an example of a BOM.

**Table D.2 Example BOM for benchmark model**

| Purpose | BOM | UOM | | Unit Price | Qty Req'd | Cost |
|---|---|---|---|---|---|---|
| Outer | Sheet metal - aluminum - 14"x25' | 29.17 | sq ft | $ 25.61 | 17.31 | $ 15.20 |
| Insulation 1 | Fiberglass - R6.7 - 2" x 16" x 48" | 0.89 | cu. ft | $ 3.94 | 0.85 | $ 3.78 |
| Insulation 2 | N/A | | | | | |
| Window | Double glass - 0.1875" air space, 18" x 18" | 2.25 | sq ft | $ 19.60 | 3.36 | $ 29.28 |
| Reflector | Mirror - 18" x 18" | 2.25 | sq ft | $ 12.60 | 1.78 | $ 9.96 |
| Structural | Wood (Douglas fir) - 2" x 4" x 20' | 20 | ft | $ 4.98 | 1.67 | $ 0.42 |
| **Total Material Cost** | | | | | | **$ 58.62** |

The results of the 10 different scenario BOM is listed in Table D.3. As noted earlier in the paper, the material costs should not be used as absolute numbers, rather to illustrate the relative cost savings as compared to the Fair Fabricators benchmark model.

**Table D.3 BOM cost summary for 10 scenarios**

| | Description | Material Cost | Savings |
|---|---|---|---|
| Model A | Benchmark model | $ 58.62 | |
| Model B | OUTER: Plywood (Sand fir) - 0.212" x 4' x 8' | $ 55.26 | 6% |
| Model C | OUTER: Hardboard - high density - 1/8" x 4' x 8' | $ 50.69 | 14% |
| Model D | INSULATION: (1/3) Fiberglass; (2/3) Foamed plastic - polysterene | $ 56.27 | 4% |
| Model E | INSULATION: (1/3) Fiberglass; (2/3) Spray - Polyurethane foam | $ 56.43 | 4% |
| Model F | WINDOW: Double glass - 0.5" air space | $ 58.62 | 0% |
| Model G | WINDOW: Double glass - 0.5" air space, low e-coating e=0.2 | $ 71.17 | **-21%** |
| Model H | WINDOW: Triple glass - 0.25" air space | $ 86.85 | **-48%** |
| Model I | O: Hardboard; I: Fiberglass, Polyurethane foam; G: Double glass | $ 48.51 | 17% |
| Model J | O: Hardboard; I: Fiberglass, Polysterene; W: Double glass w/ low e | $ 60.89 | -4% |

## D.2 Benefit Analysis

We identified two primary benefits to using the solar box cooker: 1) decreased cooking fuel expenditures, and 2) an increase in women's time, allowing for more opportunities to earn a part-time income.

*Cooking Fuel Savings*

There are five primary cooking fuels available to rural villages in India: crop residue, dung cakes, fuelwood, kerosene, and liquefied petroleum gas (LPG). We chose to focus our analysis on fuelwood savings, as rural households in Gujarat rely on wood for 65% of their cooking energy needs (India Stats, 2001).

To determine the total cooking fuel expenditures on a monthly basis, we used cost estimates (Rs/kg) provided by HEDN Household Energy and then multiplied this cost by the monthly household requirements. The result was a total monthly fuelwood expense of 171 rupees.

However, the solar box cooker is limited to lunch meals on sunny days. To adjust the monthly fuelwood expense, we approximated the fuel usage for each meal (breakfast: 20%, lunch: 35%, dinner: 45% of daily cooking fuel consumption) and the percentage of food that could be cooked in the solar box cooker (80%, because roti and fried foods cannot be cooked in the SBC). These percentages were then validated through interviews with Gujaratis and other Indians. The end result was a 28% monthly fuel decrease through usage of the solar box cooker.

Finally, we needed to adjust for seasonal (monsoon season) and weather fluctuations (cloudy days). We estimated that solar cooking in Gujarat was possible 300 days out of the year (Dave, 2008).

*Increased Employment Opportunities*

We calculated the opportunity cost of women gathering fuelwood on a daily basis by using data from Bina Agarwal's 1986 study (Sen, 2003). The average amount of time spent collecting wood in Gujarat is five hours, with approximately 15 trips per month. This translates to a total monthly collecting time of 75 hours.

In most rural communities and in particular for women, employment tends to be in the informal sector. Therefore, it was difficult to gather information about hourly salary costs. As a result, we used the cost of fuelwood (5.5 rupees for a 20kg of wood) as a potential income proxy (Agarwal and Deshingkar, 1983).

Assuming that women could work 25% days out of the month, we calculated the potential income opportunity by multiplying the "fuelwood salary/day" by the number of daily trips per month by the percentage of days that women could work. The final result was a 20.625 rupees monthly salary.

## D.3 Net Present Value / Annual Levelized Cost Analysis

The final portion of our analysis was calculating the net present value and annual levelized cost for the material cost of each scenario. We used a discount rate of 100% for the rural poor in India, based on conversations with our mentor and GSI. As well, we assumed each solar box cooker had a lifetime value of 10 years although some metal versions have lasted 20-30 years due to their high durability. Finally, we assumed a salvage value of 2USD per device as the scrap metal could be recycled and re-sold.

Using these assumptions, we calculated the net present value for the ten-year period and then transformed the NPV of the costs into a constant annual cost value over the lifetime of the project. Due to the high discount rate, the initial cost of the device was effectively incurred by the user every year.

While the model accurately calculates NPV and ALC for the solar box cooker device, unfortunately the results are inconclusive and not included in the report. The high material costs are based off US retail prices with BOMs ranging from $50 to $85 USD. These numbers are not indicative of bulk procurement prices in India and thus cannot be used as a proxy for understanding the real annual levelized cost for the user.

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*Appendix E. Interview Questions – Solar Box Cooker Users*

The following questions were used to ensure consistent content coverage during interviewing:

- What prompted you to buy the solar box cooker in the first place? What were your primary alternatives?
- Can you walk us through a typical solar box cooker experience from deciding what to eat to cleaning up?
    - Kind of box cooker
    - Setup
    - Foods typically cooked
        - Tied to religious/cultural beliefs
        - Amount of food
        - For how many
        - Communal aspects
    - Length of time for food be cooked for
        - Variability
        - Issues
    - Typical times of usage
    - Cleaning
    - Storage
    - Safety
- Can you comment on the durability of the device?
- Did you use your solar box cooker for any other purposes besides cooking meals?
- Was your solar box cooker a permanent fixture or was it moveable? How did that work out?
- What came to mind when you saw the aesthetics of the solar box cooker?
- What did your neighbors and friends think of the solar box cooker?
- What did you like or dislike about using the solar box cooker?
- What do you think prevents others from adopting this technology?