Domestic Solar Water Heater for Developing Countries

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ABSTRACT

Obtaining hot water is energy intensive. In developing nations, heating water for bathing and cooking is often the most expensive and time-consuming process in the household energy budget. Solar hot water systems could present a sustainable solution for poor households if the upfront prices of these systems were competitive with current methods. Our team is developing a low-cost residential solar hot water system for developing countries. This system will be installed into existing water plumbing and provide 100 liters of 40˚C water for early morning bathing. The system will be constructed using local materials and labor to minimize cost and maximize impact.

Initial prototypes were built and tested at Lawrence Berkeley National Laboratory in Berkeley, California for initial implementation in Quezaltenango (Xela), Guatemala. Initial testing demonstrated the ability of the system to heat up 100L of water to 40°C by 2:00pm. The water temperature was at 30°C the next morning. The current price of the hand-built prototype is estimated to be $224 (chicken wire absorber prototype) and $234 (wavy, galvanized steel absorber prototype); however further prototype optimization will significantly decrease the final cost to under the goal of $200 hand-built ($100 mass produced). Additional prototype testing is required for further optimization of the model.

1.0 Introduction

Heating water dominates the energy needs of households worldwide. In US households, heating water is second only to heating and air conditioning in energy consumption [1]. For households in developing nations, heating water is often the most energy intensive process, and therefore the most expensive or time-intensive.

In communities throughout the developing world, poor households struggle to meet their hot water needs. Some households rely on biomass to heat water. In many countries demand for fuel wood is one of the principal contributors to deforestation [2]. Others rely on electricity or liquid fuels such as propane to heat their water. These fuel options are unsustainable as they are costly to households and contribute to the buildup of greenhouse gases in the atmosphere. Many communities face limited or intermittent access to fuel and/or electricity, limiting their ability to access hot water for hygiene and domestic uses.

One potential solution to this problem is the use of solar energy to heat water. Solar water heating technology is used in many parts of the world including the U.S., China, India, and the Middle East. Systems have been adopted for a wide range of use patterns and climate conditions. However, most existing systems are geared toward wealthy clients. These systems often include sophisticated pumping systems and advanced materials. While these systems are profitable to their developers, they are often far beyond the financial constraints of households in poor communities of developing countries.

Today, engineers and scientists can harness solar energy with common materials and basic technologies. The simplest version is the batch solar water heater, consisting of a water tank, a dark absorber to capture the sun's radiation effectively, and a sheet of glass to create a greenhouse effect. Water enters at the bottom and is 'baked' in the sun. As it warms, hot water travels to the top of the tank due to its lower density. When the water is ready for use, cool water is supplied to the inlet and hot water flows out the top. Batch heaters systems can also include insulation to help maintain the temperature of the heated water.

Access to a low cost solar water heater would provide numerous benefits to households in developing communities. Many households could reduce their fuel costs by eliminating or reducing their need for wood, gas or electricity to heat water. Substituting traditional fuel sources with solar energy would reduce carbon emissions. According to a lifecycle analysis conducted in Australia, domestic solar water heating systems can produce net greenhouse gas savings in 2.5 – 5 years [3]. Further, reducing biomass consumption would relieve stress on depleted forests. There are also health benefits associated with solar hot water due to lessened exposure to toxins and pollutants released from burning fuels. By enabling access to hot water, households could improve their health and hygiene.

2.0 *Targeted Community*

The team had to choose among four countries for the initial location of implementation of the solar water heater: Guatemala, India, Tahiti and Sudan. The countries were selected based on local contacts connected to the course. Guatemala was finally chosen since Alissa Johnson, associate researcher, will be interning summer 2007 with a non-governmental organization (NGO), the Appropriate Infrastructure Development Group (AIDG) in Quezaltenango (Xela). Xela is the second largest city in Guatemala. Accordingly, the targeted community for initial implementation of the prototype was set to be urban households in Quezaltenango (Xela), Guatemala.

There are two main seasons in Xela; the rainy season is May through November and the dry season is December to May. At 2333m in elevation, Xela is located within a mountain valley [4]. Ambient temperatures range from 10-18°C [5] in the day and 7°C in the night [4]. Xela is consequently a challenging area for solar water heaters; however, there is a potential market and need for inexpensive water heating methods such as solar water heaters.

The team is collaborating with a non-governmental organization (NGO), the Appropriate Infrastructure Development Group (AIDG) in Quezaltenango (Xela), Guatemala for field tests of the initial prototype design and future manufacturing. The project aligns well with AIDG's mission to provide rural villages in developing nations with affordable and environmentally sound technologies to meet basic needs and break the poverty cycle. AIDG has worked on a solar water heater in the past. Their system was a separate collector/storage system that utilized a lot of expensive materials and labor. As such, their solar water heater system was too expensive for their target low-income communities, refer to Figure 1. AIDG have a workshop in Xela that employs local people. We plan to utilize this workshop for the initial implementation of the prototype [6].

Figure 1: Separate storage tank and collector solar water heater system of AIDG. The above system was too expensive for low-income communities in Xela, Guatemala.

3.0 Project Goals

3.1 Minimum Goals

The minimum goals of the project were:

(1) Design, build, and test a solar water heater that provides 100L of 40°C water by 4pm at a final cost less than $100 using local materials and labor.

(2) Evaluate the performance of the solar water heater prototypes; ensure easy construction, repair, and maintenance.

(3) Identify financial constraints of target market.

(4) Identify opportunities to offset the target markets' financial constraints (e.g. carbon offsets or bank financing) to reduce the per unit cost to customers.

3.2 Optimum Goals

Ideally, the project would design a solar water heater that would meet all of the minimum design goals and be able to retain the hot water overnight for early morning showers. In addition, the project would implement the financial options researched.

4.0 Methodology and Procedures

4.1 Literature Review

There are two main types of solar water heater systems: passive and active. Active systems integrate pumps and rotary elements and are therefore very expensive. Passive systems use natural water circulation, gravity, and/or pressurized water systems. Passive solar water heater systems are much less expensive than their active counterparts and are easier to maintain and repair. Consequently, passive systems are more suitable for low-income communities and are the focus of the following literature review [7].

Solar water heater systems can further be broken into two more design options: integrated storage-collector systems and separated storage-collector systems. Integrated storage-collector systems have the solar collector and water storage as one unit. Separated storage-collector systems separate the water storage from the solar collectors and are able to maintain the water temperature with a highly insulated storage tank. A subset of the integrated storage-collector system is the batch system. Batch solar water heaters do not allow for recirculation of the water; the water makes one pass through the solar collector.

Hussain Al-Madani studied a batch solar water heater in Bahrain consisting of an evacuated, cylindrical glass tube. Water runs through copper coils, which act as collectors, located within the glass tube. Side-by-side testing of prototypes resulted in a maximum temperature difference between the inlet and outlet of the cylindrical batch system of 27.8°C with a maximum efficiency of 41.8%. Al-Madani determined the cost of manufacturing the cylindrical batch system to be $318, slightly less expensive than typical flat plate collectors of $358 [8].

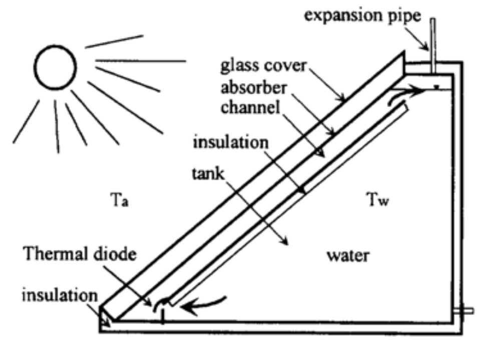
In comparison, Y. Tripanagnostopoulos and M. Souliotis experimented on optimizing an integrated storage-collector batch solar water heater that contained two cylindrical tanks and a compound parabolic concentrator made of aluminum mylar glazed with an iron oxide and black matte absorbing surface. Tripanagnostopoulos and Souliotis found that this system had high thermal losses and suggest the use of a selective absorber, double glazing, and transparent insulating material. It was concluded that this system was more complicated to build; however, the separation of the water mass from the non-uniform distribution of solar energy can result in better performance and significant water stratification [9].

A simpler batch solar water heater was investigated by F.O. Akuffo and A. Jackson in Ghana. The integrated storage-collector unit was a rectangular galvanized steel box with a total storage capacity of 90L. “Angle iron” was used to support the edges and prevent buckling and jute fiber was used for insulation. This design achieved a maximum temperature of 45°C by 4:30pm and provided 30°C water at 5:30am the next day. Daily ambient peak temperatures exceeded 37°C. Akuffo and Jackson recommend transferring the heated water to another, more insulated storage tank to lessen overnight heat loss [10].

A similar system was studied by M. Asif and T. Muneer, except their rectangular integrated storage-collector unit incorporated fins to improve thermal performance and structural stability. The unit was made of stainless steel sheets painted matte black, with four stainless steel fins. The integrated unit was surrounded on the bottom and sides with 0.05m glass wool insulation and placed in an outer wooden box. When compared to a finless (plain) model, the finned integrated system was found to be more efficient. Asif and Muneer found that the manufacturing cost for the plain model was $112 whereas it was $120 for the finned model. A carbon analysis on the manufacturing process of the system was also undertaken by Asif and Muneer [11].

Another integrated storage-collector design was investigated by A. A. Mohamad. This design consisted of a tank with a trapezoidal cross section with an inclined (37º), matte black front face. The unit is covered with a sheet of glass maintaining a 2.5cm air gap between the painted surface and the glass; all other sides of the tank are insulated with 5.0cm of Styrofoam boards. A thermal diode is made of Plexiglas (with a strip of insulation behind it) and installed parallel to the painted sheet and forms a 2.5cm channel for water. The thermal diode is used to prevent reverse circulation at night time (see Figure 2). Mohamad found that the thermal efficiency is comparable to conventional systems, estimated at 50%. Maximum average water temperature was 42ºC at 5:00pm with an ambient temperature approximately 35ºC; 5:00am water temperature was meausred to be 34º with an ambient temperature approximately 18ºC. Mohamad found that the thermal diode yielded a 10% improvement in maintaining the water temperature overnight when compared to a control prototype with no diode [12].

Figure 2: Schematic of the thermal diode integrated solar collector-storage tank system analyzed by A. A. Mohamad [12]



A separated storage-collector system was studied by N. M. Nahar. This system consisted of a flat-plate collector made of galvanized steel tubes attached to an aluminum plate with MAXORB selective surface and a double walled 100L galvanized steel storage tank. Glass wool insulation was used to insulate the storage tank. The storage tank is located up gradient from the collector. This system relies on natural circulation to drive the hot water into the overhead storage tank and allows for cold water to re-circulate to the collector. Nahar found that this system can produce 60.6ºC water at 4:00pm and 51.6ºC water the next morning. The overall efficiency of this system was determined to be 57% [13]. In an earlier study, Nahar found that the price of this system with a galvanized steel-aluminum collector ($160) was considerably less that that with a copper-copper collector ($205) while both had comparable performance [14].

A similar separated storage-collector system was studied by Zerrouki et al. in Algeria. This system had a copper plate absorber with steel connector pipes and storage tank, and a header-riser flat collector. This system also relied upon natural circulation to store the hot water in a tank located up gradient from the collector. The maximum temperature was observed to be 57ºC starting from an initial temperature of 17ºC at 7:00am. A maximum flow rate occurred at 1:00pm [15].

4.2 Design Selection

A passive system was selected as the basis for the design for this project. Passive systems do not necessitate any electricity and rely only on natural circulation of hot water, gravity feed, and/or the city water pressure. The potential drawback with such a system is its inability to provide enough pressure to get a good flow of water through the shower head. Furthermore, although the literature showed that separated storage-collector systems obtain higher water temperatures for morning showers, an integrated storage-collector batch system was chosen due to the smaller amount of materials needed (lower cost). To evaluate the option of a passive system we conducted experiments to estimate the pressure required for a system that relies solely on gravity.

Gravity flow experiments consisted of a water tank with a spigot attached to a hose. The hose had a showerhead attached at the outlet end at a height of ~10ft from the water level within the tank; 10ft corresponds approximately to the roof-to-living area height in a typical house. Flow was measured through different showerheads by obtaining the volume of water (approximated through weight measurements) after a measured period of time (see Figure 3). The results are given in Appendix A. The flow rate measured ranged from 1.44 to 3.79L/min (0.381 to 1.00gpm), depending on the shower head used. These results were considered to be satisfactory considering typical showerhead flow rates are at ~2gpm at 60psi [16]. In conclusion, gravity provided sufficient pressure if the appropriate showerhead was used, thus a low cost passive system was determined to be a viable design option.

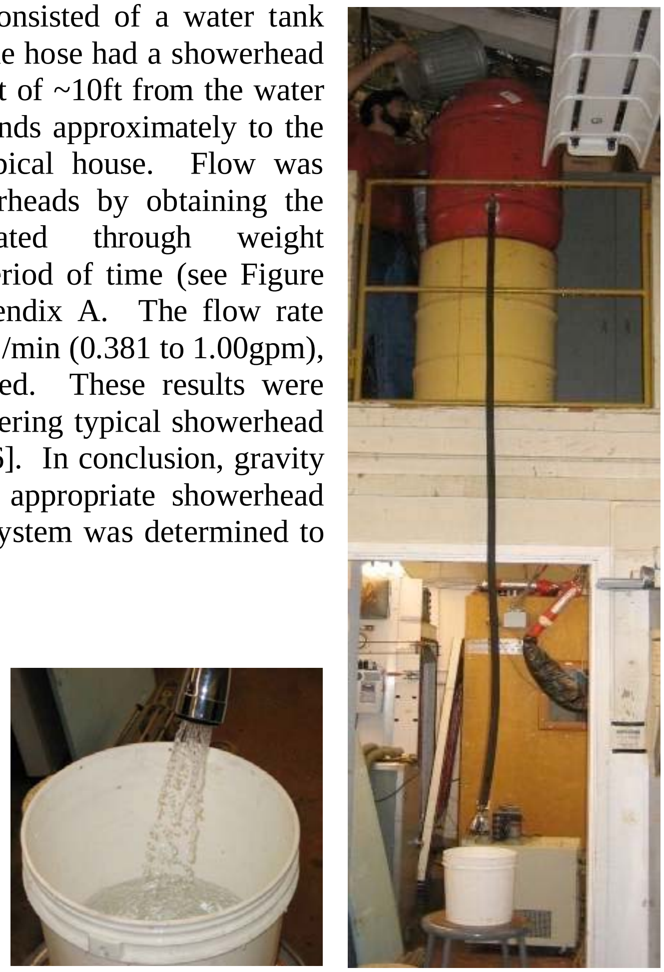


Figure 3: Gravity feed experiment held at the Lawrence Berkeley National Laboratory, March 2007.

4.3 Consumer Survey

A consumer survey was created to determine end-users' current showering/bathing habits, consumption patterns and needs, and ability to afford a solar water heater in Xela, Guatemala. The survey includes questions about the house characteristics (roof type, yard area, exposure to sunlight), water sources and distribution methods, current hot water sources and methods, and showering/bathing habits. The survey will be administered by a local representative in Xela who will conduct interviews with and collect data from 50-80 households. We are currently awaiting approval from the Committee on the Protection of Human Subjects at the University of California, Berkeley (See Appendix B for the survey).

4.4 Trip to Quezaltenango (Xela), Guatemala

Funded by a grant from the UC Berkeley Blum Center, the team was able to send one of its members (Merwan Benhabib) to Xela, Guatemala for one week in April 2007 to obtain on-the-ground information on materials, assess the local demand for a solar hot water system, and learn about their bathing/showering habits. Benhabib explored Xela's building and manufacturing capacities by visiting hardware stores and compiling a list of local materials and prices. Readily available and inexpensive materials in Xela include wire cage, garden hose, wavy metal roof tiles, glass, and high density polyethylene (see Table 1). He also found that people usually take daily showers early in the morning (between 5am and 8am), as it is a Mayan tradition and symbolic of religious purification. During the winter season, when water in the mornings is especially cold, families frequently get sick. The water plumbing in households is only for cold water. To heat water, families use an in-line electrical showerhead heater that is expensive to use due to the high cost of electricity. Households often have a limited electrical power supply (there are frequent power outages), making the in-line heaters an unreliable method to deliver sufficient hot water. Overall, the trip confirmed the need for a low cost solar water heater.

Table 1: Material Pricing in Quezaltenango, Guatemala

Material	**Price** ($1 = 7Quetzales)	**Description detailed**
Wood, plywood	4ftx8ftx1/4" 104Q 4ftx8ftx3/4" 154Q 4ftx8ftx1/2" 173Q	
Wire cage	2Q/yd	Square wire mesh gage
	4 - 7Q	Trapezoidal wire mesh gage
Garden Hose	122 Q for 75ft 86Q for 50ft	Knitted reinforced 1/2" with brass coupling connection
Roof Tiles	6.55Q per ft	Wavy roof structure; undulated A-70 Galvanised 33" wide
Black Chalkboard Paint	87Q for a gallon	Brand: Protecto Dekativo negro
Glass	170Q (5mm thick) 104Q (3mm thick)	Glass window with 1.25m2 dimensions
High Density Polyethylene	4mil thick 0.2Q per ft 6mil thick 0.3Q per ft	PlasticLandia or PasticMundo
Vinyl	~10mil thick 0.4Q per ft	
In-line Shower Heater	132Q	Medium quality; Calentador Electrico Lorenzetti 110 Vol Maxi Ducha

5.0 Design Implementation

5.1 Materials and Dimensions

The prototype design consisted of a water bladder contained in an inner case for structural support and covered with a sheet of metal (or chicken wire) that functions as an absorber and restrains the bladder; the inner case is located inside a larger case that is filled with insulation. A sheet of glass is secured above the absorber to allow for a greenhouse effect, increasing the heat transfer from the solar radiation to the water (see

Figure 4). Prototype materials were chosen based on availability in Berkeley, CA, availability in Xela, Guatemala, price, and performance (see Table 2). All prototype materials were purchased at local hardware stores near Berkeley, CA (Home Depot, Orchard Supply Hardware, and Arrow Glass). Detailed schematics of the prototype design are provided in Appendix C.

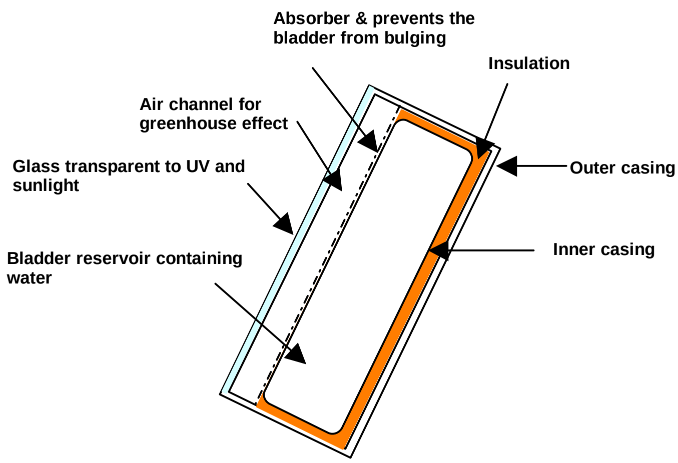


Figure 4: Schematic of the batch solar water heater prototype.

Table 2: Prototype Materials and Attachments for Absorber Test

Prototype Component	Material	Attachment
Inner Case	Plywood (3/8" thick) and 2"x6"	Wood glue and screws
Outer Case	Plywood (3/8" thick), 2"x4", 2"x2", and 2"x6"	Wood glue and screws
Absorber	Wavy galvanized steel sheet metal and chicken wire	Screws and staples
Water Bladder	6mil, high density polyethylene (1mil = 0.001in)	Heat sealed
Insulation	Packing peanuts and expanded polystyrene foam	Spray adhesive
Glass	31.5" x 55.5" x 3.8"	Slid into grooves cut into outer case frame and taped closed at top
Connections	Garden hose	"MacGyver" floss

5.2 Prototype Building

Two prototypes were built: a test prototype to vary a parameter and a control prototype to compare the performance and cost to a simpler/cheaper design. Prototypes were built and tested at Lawrence Berkeley National Laboratory with the guidance of team mentors Howdy Goudey and Jonathan Slack. The team completed the prototypes over the course of 2-3 weeks.

Water bladders were prepared by heat sealing the high density polyethylene sheets into a rectangular shape with an inlet and outlet located at opposite sides (see Figure 5). Garden hose served as the inlet/outlet of the water bladders and sealed by tightly wrapping thin "MacGyver" floss around the bladder and hose (see Figure 5). Inner and outer cases were built as wooden rectangular boxes. The inner case had a plywood bottom and 2"x6" sides. The sides were screwed and glued onto the plywood bottom (see Figure 6). The chicken wire absorber was installed by tightly stretching the chicken wire over the inner case and stapling it to the sides of the inner case. The wavy, galvanized steel sheet absorber was installed by screwing the sheet onto the top of the inner case. Once installed, both absorbers were painted matte black using chalkboard paint. The outer case had a plywood bottom and sides. A frame was made of 2"x4" pieces that were grooved to insert plywood sides and bottom. A smaller top frame made of 2"x2" was attached to the top of the outer case sides by grooving the frame and sliding the plywood sides into the notches (glue was added to the grooves before inserting the plywood sides). This top frame was also grooved to support and hold the glass sheet (see Figure 7). Holes were drilled into the sides of both inner and outer casings for the inlet and outlet. The glass sheet was slid into the top frame groove of the outer case and taped closed at the top of the prototype. Prior to the glass installation, strips of hard, expanded polystyrene foam were glued to the inside of the outer case in areas to support the inner case. The inner case was placed inside the outer case and packing peanuts filled the spacing between the inner and outer case (see Figure 8). High density polyethylene was stapled to the outer and inner case to hold the insulation in place. Figure 9 shows the completed prototypes.

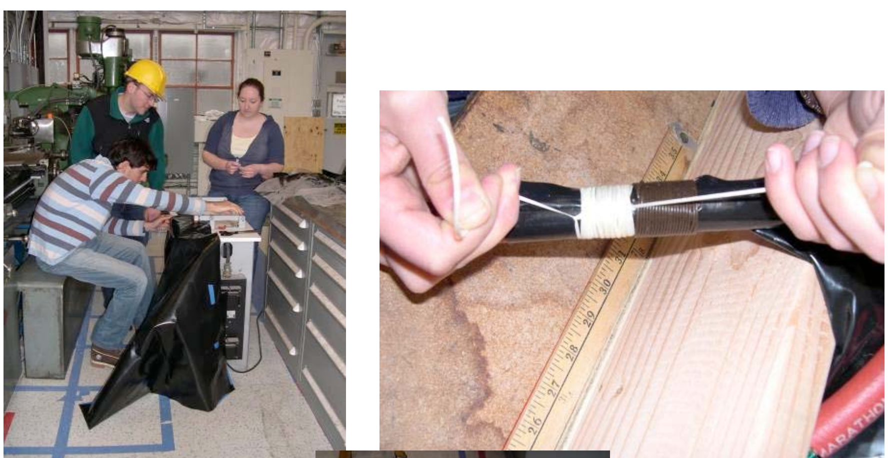


Figure 5: (Left) Heat sealing the high density polyethylene into a water bladder and (Right) inlet/oulet seal.

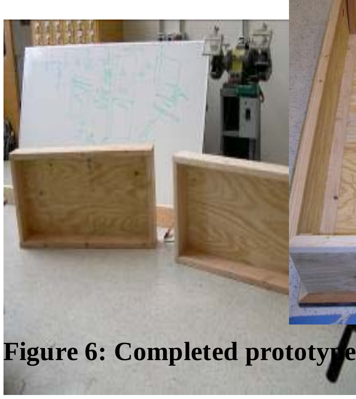


Figure 6: Completed prototype inner cases.

Figure 7: Completed prototype outer case.

Figure 8: Insulation layer filling the spacing between the inner and outer casing.

Figure 9: Completed prototypes (chicken wire absorber on the right and metal absorber on the left).

5.3 Prototype Testing

Performance tests evaluated the time required to heat up the water to 40˚C and if the system could retain that temperature overnight. Test variables were the absorber and insulation materials. The absorber test was completed Apr 28 - May 3, 2007. Side-by-Side tests compared two absorbers: a wavy, galvanized steel sheet (test prototype) and chicken wire (control prototype). The purpose of the initial absorber test was to determine if the galvanized steel sheet was necessary to heat the water in the bladder or if the painted chicken wire and water bladder were sufficient. Both prototypes had packing peanuts as insulation.

Based on the literature review, the design must be tilted at an angle of 15° plus the degree of latitude of the location [13] to maximize solar incidence.[1] The prototypes were setup side by side tilted at a 48° south-facing angle (5° less due to the time of year testing was done). Nine Type T thermocouple wires connected to a data logger were used to collect temperature readings at 5min intervals during the test. The thermocouples were located at the back of the inner casing in contact with the bladder at three locations for each prototype(10cm from the top of the inner case, 10cm from the bottom, and at the center), on each of the absorbers, and above the prototypes for ambient readings.

The bladders were each filled up with water by connecting a garden hose to the inlet. The bladders were filled up to the point when an obvious bulging occurred and the steel sheet and chicken wire began to deflect. The deflection occurred near the center and lower-third section of the absorbers; deflection occurred in both absorbers. Data collection began at 10:30am on Saturday April 28, 2007. The weather was sunny with light, thin cloud cover. The next morning at 7:00am, the team drained each of the

[1] Xela is at 14.83°N latitude, so the solar water heater would need to be at a 30° angle. Berkeley, CA is at 37.87°N, so the prototype would need to be placed at a 53° angle during testing.

bladders to determine the water volume, water thermal stratification in the bladders, and if a temperature of 40°C was retained overnight.

At approximately 5:00pm on Saturday, it was observed that the chicken wire prototype had a leak at the inlet. By the next morning, the water level was about 20cm lower than the top of the inner casing. Consequently, the thermocouple at the top of the inner casing was not completely in contact with the bladder, thus the temperature readings were affected by the ambient temperature. A direct comparison between the two data sets could not be undertaken.

5.4 Absorber Test Results and Analysis

Figure 10 shows the temperature rise of each of the absorbers over the course of the testing period (10:30am on Saturday till 7am on Sunday). Both absorbers gave comparable results in terms of achieving a maximum temperature close to 60°C by 5pm. The thermal losses were also comparable as both absorbers were at 30°C the next morning in a 10°C ambient overnight.

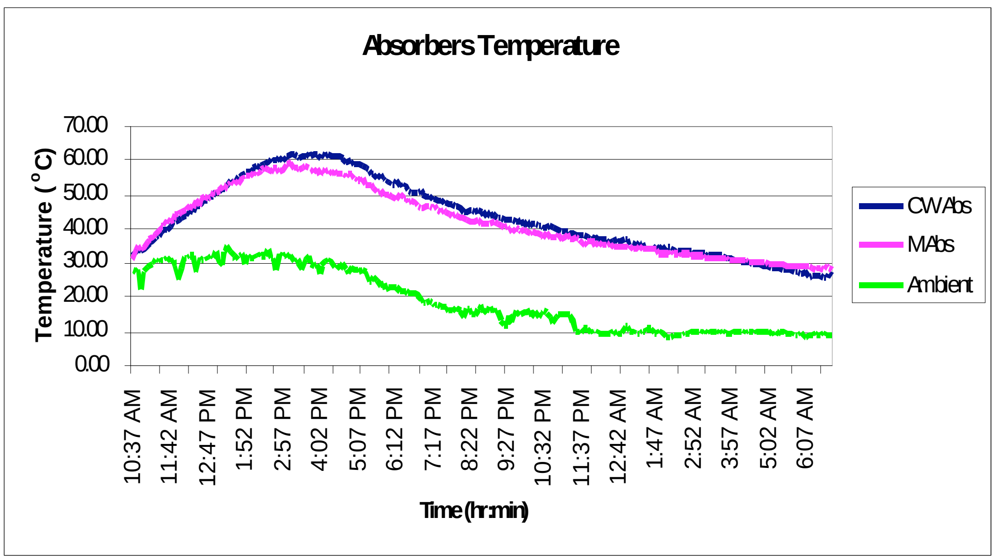


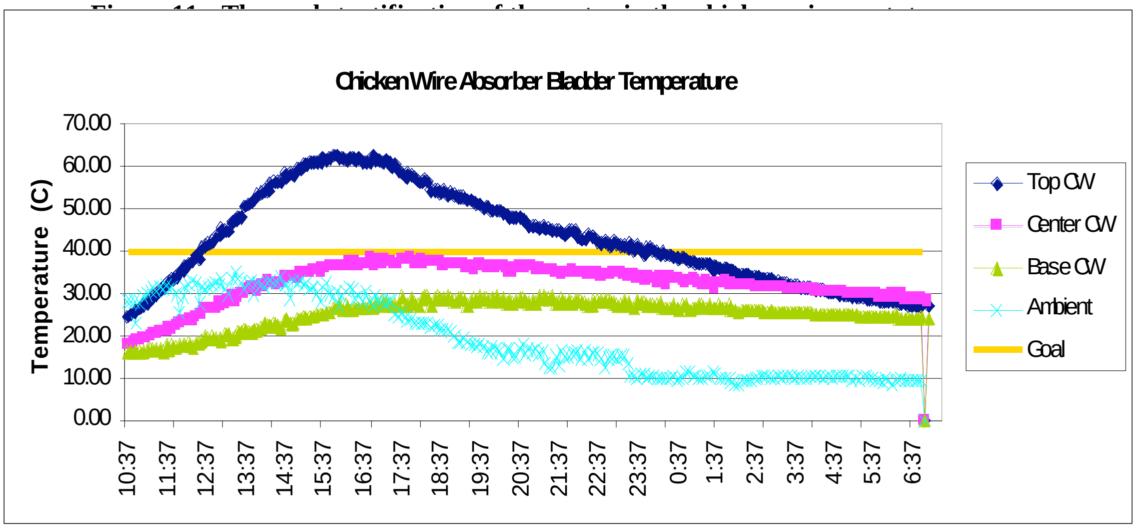
Figure 10: Comparison of sheet metal absorber (M Abs) to the chicken wire absorber (CW Abs) temperature rise with respect to ambient temperature.

Since the thermal performance results of the absorbers were comparable, a qualitative comparison was needed to assist in evaluating these two options (see Table 3).

Table 3: Advantages and Disadvantages of the Two Absorbers Tested

	Wavy Galvanized Steel Wavy Sheet Metal Absorber	Chicken Wire Absorber
PROS	- Structural support - More resistant to deflection	- Extremely low cost
	- Easier to install and paint	- Labor intensive (good for local labor market)
CONS	- Uncertainty in air gaps between absorber and water bladder	- Less structural support
	- Less labor intensive	

In terms of the thermal stratification of the water in the bladder, Figures 11 and 12 illustrate the temperature change over the course of the day and night for each of the prototypes. Due to the slow leak at the inlet of the chicken wire prototype, a smaller volume of water was heated thus a higher thermal stratification was measured. In addition, there was a steeper decrease in temperature after 5:30pm due to the exposure of the thermocouple to air. Accordingly a direct comparison of the results could not be made. Nevertheless, key observations are that both prototypes heated up the water to 40°C, the target temperature, by 2pm and maintained it till ~10pm. The water temperature dropped to about 20-30°C the next morning, which was 10-20°C above ambient.



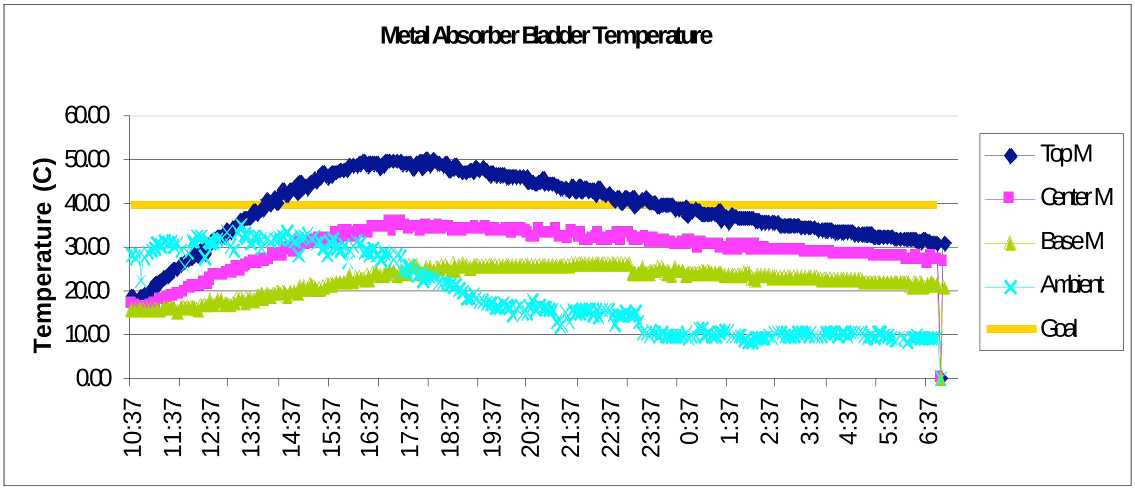


Figure 12: Thermal stratification of the water in the metal absorber prototype.

When the water was drained on Sunday morning at 7-8am, there was a morning fog with an ambient of 10°C. The bladders were drained out into 50L carboys. Thus, the water volume was measured to be 100L for the chicken wire prototype and 113L in the metal absorber prototype. Additionally, the water temperature varied between 24-30°C in the chicken wire prototype and 21-30°C in the metal absorber prototype (Figure 13).

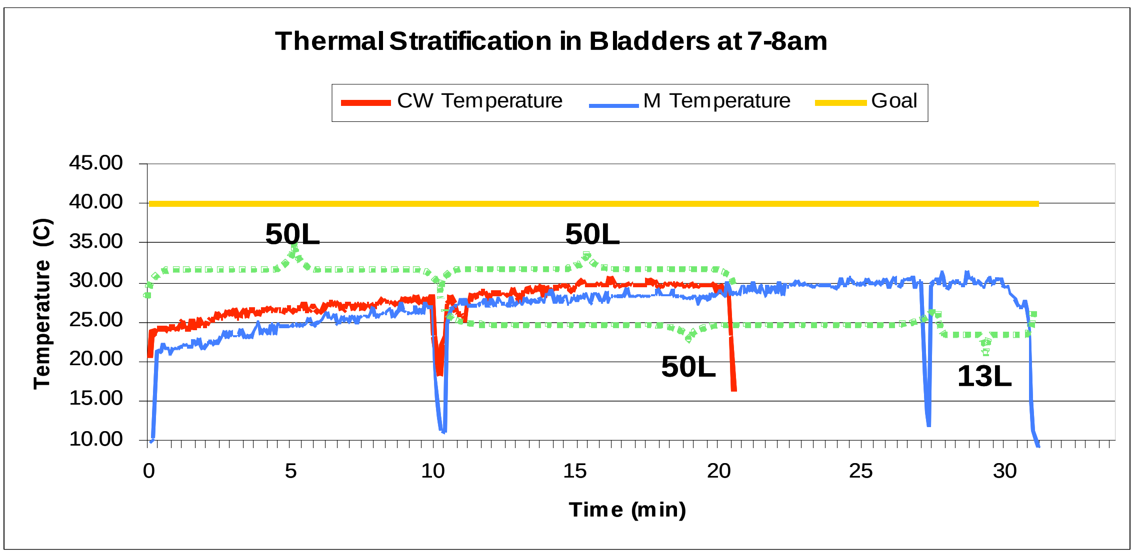


Figure 13: Temperature readings upon draining each of the bladders.

Heat loss calculations based on these results demonstrated that there was an average of 63W (38W/m^2) thermal losses to the ambient in the wavy galvanized steel absorber prototype and a 61W (41W/m^2) thermal losses to the ambient in the chicken wire prototype. This corresponds to an R-value of 0.17 (K.m^2/W) for the wavy, galvanized steel absorber prototype and 0.19 (K.m^2/W) for the chicken wire absorber (see Appendix E for calculations).

Both of the absorbers appear to be comparable in performance; however, conclusive direct comparisons can not be made due to the leak in the chicken wire inlet.

The target temperature was reached in both prototypes with estimated R-values of 0.17and 0.19 for the metal and chicken wire absorber respectively. Although the chicken wire absorber is much less expensive, the wavy, galvanized sheet metal absorber provided slightly more resistance towards deflection. Future tests will require water-tight inlets and outlets to yield comparable results between models.

5.5 Next Steps in Testing

Future tests will focus on the durability of the water-tight seals for the inlet and outlet. A series of long bladder "nozzles" attached to short pieces of hose, will be used to test a large number of joints simultaneously under the same pressure. This experimental setup will allow for exclusive inlet/outlet seal testing and avoid complications of solar collection testing. Additionally, an improved device is needed to prevent absorber deflection and better restrain the bladder. Experiments on the bladder restraint will be done in a similar manner, using the inner case only and measuring deflection on a variety of wires (heavier gauge), fastening, and reinforcement techniques for both the chicken wire and wavy galvanized steel absorbers.

Insulation tests will be undertaken to determine the most cost-effective insulation material. Insulation test materials were chosen based on their R-values (thermal resistance), price, and availability in Xela, Guatemala. Insulation materials to be tested include packing peanuts (polystyrene), crushed packing peanuts, packing peanuts separated by layers of aluminum foil, and fiberglass. Another insulation option is the coffee byproduct native to Xela, Guatemala called *pagaso* and *pergamino*, a sample of which was collected on the recent trip to Guatemala. The control prototype in the insulation tests will not have insulation, while the test prototype will have the selected insulation of interest.

5.6 Recommended Design

Currently, both casings are made out of wood for simplicity of building the initial prototypes. Wood can not be used in the final design since it is not weatherproof and the quality of wood available in Guatemala is poor (confirmed on the recent trip to Guatemala). For the final design, we would like to conduct a proof-of-concept to demonstrate the feasibility of using galvanized steel roof sheets for both the outer and inner casings. This material is inexpensive in Guatemala and available in large quantities. Another option is to use “Ferro-cement” for the outer casing and galvanized steel roof sheets for the inner casing. Cement is weatherproof, durable, and easy to use. Results from further prototype testing will be incorporated in the recommended design that will be field-tested in Guatemala.

6.0 Cost Analysis and Financial Options –

6.1 Total Cost of Materials per Unit per Prototype

A primary goal of this project was to develop a solar water heater that sells under $100. It can be estimated that a unit hand-built in the U.S. for $200 would be comparable to a unit mass produced in Guatemala for $100. A unit selling for $100 would require material cost of under $30 per unit, in order to account for overhead expenses in the price of the final unit. Assuming that materials are generally twice as expensive in the U.S. as in Guatemala, a unit mass produced in U.S. would cost roughly $60. Mass production should reduce costs by approximately 30%; therefore, a hand-built unit would require $200 for materials in the U.S. in order to be roughly comparable to the unit costs of a solar water heater mass produced in Guatemala (see Table 4).

Table 4: Cost Estimation for Hand-Built Prototypes

Retail Price per unit in Guatemala	$100
Estimated Overhead and Business Expenses, per Unit	$70
Estimated Material Cost per Unit (in Guatemala)	$30
Estimated Material Cost per Unit (in US)	$60
Estimated Cost to Hand-build in US	$200

The estimated cost for our hand-built models exceeded the $200 ($100 mass produced) goal, however there are several opportunities to reduce these costs in future models. The cost of materials for the chicken wire prototype and the metal absorber prototype were $224 and $234, respectively (see Table 5). In each unit, the cost of glass ($94) and hard expanded polystyrene foam ($50) represent over half the total material costs. Based on the survey of material prices in Guatemala, the cost of glass would be significantly less in Guatemala (approximately $14). Economies of scale for bulk purchasing should reduce this cost even further. The hard foam estimate is based on retail prices for individually-cut foam. Bulk purchases of un-cut foam would significantly reduce its price. Incorporating these cost revisions could significantly reduce the per-unit cost below the $200 goal for a hand-built unit.

Table 5: Cost of Materials per Unit per Prototype

Item	Amount of material	Cost in US for chicken wire SWH (USD)	Cost in US for metal SWH (USD)
Ply Wood (base inner case)	1 board	6.37	6.37
Ply Wood (base, outer case)	2 boards	12.74	12.74
Ply Wood (sides)	0.5 boards	5.475	5.475
wood (2 x 4)	1 board	2	2
wood (2 x 2)	2.5 lengths	4.375	4.375
wood (2 x 6)	2 boards	8	8
corner supports	1/8 board	0.875	0.875
wavy sheet metal	1 sheet		9.48
screws	half box	3.5	3.5
Plastic for bladders		7.45	7.45
garden hose		15	15
glass		93	93
chicken wire	1/5 of roll	1.4	1.4
studs	1 box per unit	2.38	2.38
chalk board paint	0.5 can	2.5	2.5
hard expanded polystyrene foam	9 blocks per unit	50	50
peanuts	10.6 ft^3 per unit	9	9
Total (USD)		224.065	233.545

6.2 Estimated Energy Savings

A solar water heater in a typical Guatemalan household can produce an annual energy cost savings of over $27 (see Table 6). This estimate is based on water usage for a household that takes 3 showers per day. Currently, most households rely on in-line electric shower heaters which typically require 6 kW of power. Assuming that a solar water heater can provide for half of the energy needs for these showers, a household could save 410 kWh of energy per year. A survey of water use patterns by households could improve these estimates. Additional field tests would provide more detailed information on how much annual water use can be offset by a solar water heater.

Table 6: Annual Household Energy Savings from Solar Water Heater Use

	Typical Guatemalan Household (without Solar Water Heater)	Typical Guatemalan Household (with Solar Water Heater)
Estimated average shower length (minutes per day)	7.5	7.5
Average kW usage from shower head[1]	6kW	6kW
Estimated average heated showers per day	3	3
Average in-line showers per day[2]	3	1.5
Total minutes of in-line heater use per day	22.5	11.25
Total daily kWh used in showering	2.25	1.13
Total annual kWh used in showering	821.25	410.63
Total annual kWh reduced by solar water heater use		410.63
Annual Savings (in Guatemalan Quetzales)[3]		205.31
Annual Savings (in US dollars)[4]		**$27.38**
[1]assumes that a solar water heater will offset half the use of in-line heater		
[2]based on average power of commonly available in-line water heaters		
[3]AIDG estimates that electricity in urban areas of Guatemala averages 0.5 Quetzales per kWh		
[4]assumes exchange rate of 7.5 Quetzales per U.S. dollar		

6.3 Estimated Net Present Value

Using the estimated energy savings (Table 6), the net present value of a solar water heater sold for $100 in Guatemala was calculated (Table 7). Using minimal maintenance costs and a 150% discount rate, a solar water heater would fail to produce net savings for customers. However, using microfinancing will help reduce the discount rate for customers, which would help increase the perceived value of out-year energy savings. A social discount rate of 6% would allow customers to produce net savings within the 5-year life of the solar water heater.

The social net present value of a solar water heater in Guatemala is more promising. In the following analysis, an additional 10% in electricity savings was assumed to account for government subsidies used to support the electricity sector. Under these conditions, a solar water heater has a payback of under 4 years. Greater value could be attributed to electricity saving if solar water heaters could be demonstrated to relieve congestion on the electricity grid or if current electricity supplies are unable to meet current demands.

Table 7: Annual Household Net Present Value With Solar Water Heater Use

Total Household Net Present Value (At target price = $100)					
	year 1	year 2	year 3	year 4	Year 5
All values USD					
Initial costs	100				
Energy savings	-27.375	-27.375	-27.375	-27.375	-27.375
Maintenance costs			10		10
Total	72.625	-27.375	-17.375	-27.375	-17.375
Discounted	72.625	-10.95	-2.78	-1.752	-0.4448
Discount rate	150%				
Net present value					**-56.69**
Total Social Net Present Value (At target price = $100)					
	year 1	year 2	year 3	year 4	Year 5
All values USD					
Initial costs	100				
Energy savings	-30.1125	-30.1125	-30.1125	-30.1125	-30.1125
Maintenance costs			10		10
Total	69.8875	-30.1125	-20.1125	-30.1125	-20.1125
Discounted	69.8875	-28.408	-17.9001	-25.283	-15.931
Discount rate	6%				
Net present value					**17.63**

Table 8: Carbon Emissions Reductions through Avoided Electricity Use

Annual Household Carbon Savings from Solar Water Heater Use		
	Typical Guatemalan Household (w/o Solar Water Heater)	Typical Guatemalan Household (w/ Solar Water Heater)
Total daily kWh used in showering (from Table 5.3)	2.25	1.13
Total annual kWh used in showering (from Table 5.3)	821.25	410.63
Estimated average metric tons CO_2 emissions per kWh in Guatemala[1]	0.0004	0.0004
Estimated carbon emissions (tons CO_2)	0.3146	0.1573
Total CO_2 savings		0.1573
Price (USD) per ton of CO_2 emissions reduced (low)[2]		$3.00
Price (USD) per ton of CO_2 emissions reduced (high)		$20.00
Estimated price range for annual carbon reductions		**$0.50-$3.15**
[1]Does not account for losses due to transmission and distribution		
[2]Carbon price range based on 2006 European Emissions Trading System price range for 2005-2006 ("A Bargain", The Economist, 5/4/2007). Estimates used here are half the range reported to account for overhead.		

Estimates for carbon emissions avoided through the use of domestic solar water heaters are based on the average emissions from electricity production in Guatemala (see Table 9). Based on these estimates, carbon credits could produce savings between $0.50 and $3.15 annually per household. Sale of carbon offsets could be aggregated by the manufacturer of solar water heaters and used to reduce the final retail price for households. Organizations like Climate Care, Inc. purchase carbon offsets from small projects in developing countries.

Table 9: Guatemala's Energy Mix and Estimated Carbon Emissions

Guatemala's Energy Mix and Estimated Carbon Emissions (2004)				
Energy Source	Generation (GWh)[1]	Generation (MWh)	Emissions Rate (metric tons CO_2 per MWh)[2]	Total Emissions (tons CO_2)
Coal	1200	1200000	0.95	1140000
Petroleum	2505	2505000	0.6	1503000
Natural Gas		0	0.55	0
Large Hydro	2324	2324000		0
Small Hydro	0	0		0
Biomass	870	870000		0
solar		0		0
Wind	0	0		0
Geothermal	0	0		0
Nuclear	0	0		0
TOTAL	6899	6899000		2643000
Average emissions per MWh (tons CO_2)				0.38310
Average emissions per kWh (tons CO_2)				0.00038

[1]from http://www.iea.org/Textbase/stats/electricitydata.asp?COUNTRY_CODE=GT
[2]Introduction to Engineering and the Environment, Edward Rubins and Cliff Davidson 1999

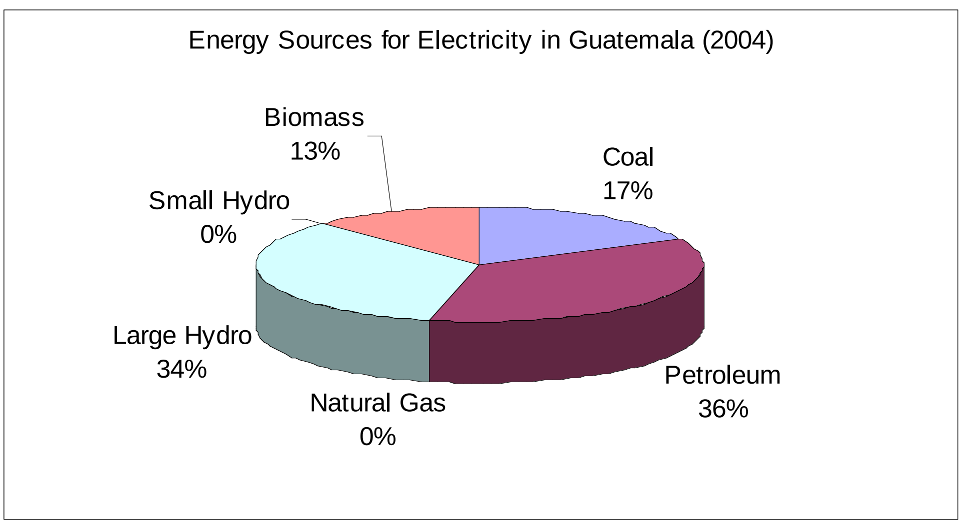


Figure 14: Data used for Table 9 calculations.
Source: International Energy Administration (2004)

7.0 Future Work

Future work will focus on further prototype testing and exploration of financing options. Additional testing is needed to evaluate insulation options and assess the performance of other low-cost materials. Moreover, analyses are needed to assess the durability of the prototype and the long term strength of the inlet/outlet seal. The current model was designed to test the performance of the bladder and insulation. However, the current wood structure is not suitable for use in Guatemala. Preliminary designs for an alternative structure include the use of galvanized steel and/or cement.

This summer, the team will use the results from additional testing to produce a revised prototype. The team hopes to test this prototype in Guatemala to determine its performance under local conditions.

Cost analysis suggests the need for financing opportunities that can reduce the up-front cost of the solar water heater. The team will explore opportunities for collaborating with microfinancing institutions and selling carbon offsets. The team has already established contact with a Guatemalan microfinancing institution, Namaste International, that has expressed interest in partnering on this project. While the carbon offsets of individual solar water heaters is minimal, opportunities for selling aggregate credits for all sales could produce a small, but important means of reducing the selling price of the model.

Solar water heating is applicable to a wide range of communities in the developing world. As AIDG expands to other countries, future work will involve modifying this design to meet the needs and materials of other regions.

8.0 Conclusion

The purpose of this project was to develop a low cost solar water heater. Specifically a solar water heater built from local materials and labor that would cost less than $100 and deliver 100L of 40°C water by 4:00pm. Based on these criteria, a batch, integrated storage-collector system was selected. Materials were selected based on cost, performance, and availability in Guatemala. Two prototypes were built and tested comparing a chicken wire absorber to a wavy, galvanized steel absorber. Both absorbers achieved 40°C by 2:00pm. However, due to an inlet leak in one prototype, repeated tests are necessary to confirm these results. Currently the prototype cost is slightly above the target. Although, there are several opportunities to significantly reduce the cost.

Future tests will focus on durability, material selection and cost reduction. A revised prototype will be tested in Guatemala (Summer 2007) and results from field experiments will be incorporated into the final design. Financing options will be further investigated. Eventually a business plan will be developed for the mass production and marketing of the product.

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Merwan Benhabib is currently a second-year UCB Mechanical Engineering graduate student with a focus in Design and Micro Electro Mechanical Systems. His research focuses on developing the design of an automated micro-fluidic instrumentation for amino acid detection. The purpose is the search for signs of extraterrestrial life on Mars: The miniaturized biochemical analysis system would be flown to the planet for in situ experimentation. The project is interdisciplinary involving design, optics, data acquisition, control, and micro-fluidics. Merwan graduated with an engineering diploma in 2005 from l'Ecole Nationale Superieure d'Arts et Metiers in Paris, France.

Adam Langton is a second-year UCB Public Policy grad student. His interests include international development and energy policy. Adam completed his undergraduate degree in economics at Boston College's Carroll School of Management. He currently interns at the California Public Utilities Commission and works on Renewable Energy Policy.

Alissa Johnson is a second-year graduate student in the Material Science and Engineering department. She studies "dirty" silicon (silicon that has not been purified to meet microelectronic standards) for low-cost solar cell applications. She is passionate about finding ways for the developing world to progress sustainably and will be traveling to Guatemala this summer to volunteer with the NGO Appropriate Infrastructure Development Group. She graduated from the University of Wisconsin-Madison with degree in Engineering and a minor in Business.