

A NEW GENERATION OF SENEGALESE SOLAR OVENS

FINAL REPORT

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EXECUTIVE SUMMARY

This report details the work completed by the authors during the summer of 2004 as interns for CRESP, a non-governmental organization based outside of Dakar, Senegal, while volunteering for Engineers for a Sustainable World (ESW). The work consisted primarily of redesigning a locally available solar oven with the goal of making it more affordable for rural communities. The project culminated in a functioning prototype, fabricated primarily of recycled plastic, which preliminary test results indicate outperforms the existing model. The report includes an introduction to the solar cooking movement in Senegal and describes the urgency of widespread implementation due to deforestation, desertification, and health related issues. User research, brainstorming, concept selection, detailed design, prototyping, experimental processes, and calculations employed by the authors are also documented. A novel replacement of wood with plastic recycled from local communities is discussed in detail and timelines, budgets, drawings, and personal reflections are presented as appendices. In addition to the oven project, included are descriptions of two secondary projects completed during the course of the summer, the design installation of a rainwater collection system and a geometric specification of a rooftop solar water heater. This document is intended to provide support for any future effort at commercializing the prototype.

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In the summer of 2004, we interned as Engineers for a Sustainable World (ESW) volunteers at CRESO (Centre de Ressources pour l'Émergence Sociale Participative), a non-governmental organization (NGO) in Yoff, Senegal. Originally assigned to a different project in Nigeria, we were re-staffed to Senegal four days before our departure. Prior to arrival, we had a rough idea of our project's theme, solar ovens, but no clear concept of its eventual direction. Having had little time to prepare, we were quickly immersed in the cultural, linguistic, and technical landscape that would frame our summer's work.

PROJECT BACKGROUND

Solar ovens have been successful in many parts of the world. They use the power of the sun, solar radiation, as their sole source of energy for cooking. During most of the year Senegal receives intense solar radiation, making it an ideal candidate for solar cooking.

In villages throughout Senegal, cooking is typically done over a wood fire, resulting in obvious peril, namely deforestation and subsequently desertification. With less arable land available and diminishing soil quality, the Sahara creeps southward, slowly consuming the Senegalese savannah. Rural families must travel deeper into the bush to collect firewood or else rely on the government's bottled fuel that is increasingly difficult to afford. Improperly extinguished cooking fires in the bush commonly lead to forest fires, furthering the loss of vegetation. Additionally, the daily exposure to smoke while cooking is a common cause of blindness and chronic respiratory problems.

Beyond health, environmental, and economic benefits, solar ovens stand to enable enormous social and nutritional change in Senegal and across West Africa. The food is generally healthier, since most solar ovens are incapable of frying. In traditional cooking methods, women tend to the food throughout the whole cooking process, but with a solar oven, users can simply place the meal inside and return when it is finished.

Abdoulaye Touré is one of West Africa's leading solar cooking advocates. Currently the president of CRESO Senegal's EcoVillage in Méckhé, he has promoted the use of solar ovens in and around Senegal for approximately 20 years. His current solar oven is an adaptation of designs from NGO Bolivia Inti, ULOG, and SunOven. This oven exists in both the first- and



Figure 1: First-Generation Solar Oven

second-generation designs pictured in Figures 1 and 2, respectively. Like its predecessor, the second-generation oven is a wooden, box-type solar cooker, with an aluminum liner insert that is painted black to absorb heat from incoming sunlight. On top of the cooking box is a window frame that outlines a pair of openings, each of which contains two layers of glass. To the window frame, Touré attaches a single wooden reflector, covered on one side with aluminum foil.



Figure 2: Second-Generation Solar Oven

Touré employs novel features for aiming and adjusting the oven to gather the maximum amount of solar energy and therefore reduce cooking time. There are two small mirrors located at the two outer corners of the reflector. When these mirrors cast spots of sunlight on the far corners of the window frame, the oven is correctly oriented. When properly adjusted, all the sunlight that hits the reflector is directed into the box through the window frame. A wooden strut is placed in various holes drilled into the reflector and window frame to prop the reflector at discrete angles. A tensioned string keeps the reflector held tightly against the strut. Together, these features indicate when the oven is improperly adjusted and allow it to be easily re-aimed for maximum thermal efficiency.

In the past two years, Touré has identified capital cost as the biggest roadblock in promoting wider distribution of solar cookers. Touré believes that ovens must be affordable for rural communities without significant financial subsidization. To date, foreign and domestic aid has enabled user trials in villages ranging from Senegal’s northern border near Mauritania to its southern region of Casamance. His current second-generation model meets most user expectations, but costs 50,000 CFA (~\$100 USD) per oven. As shown in Figure 3, most of the cost results from the use of wood and glass.

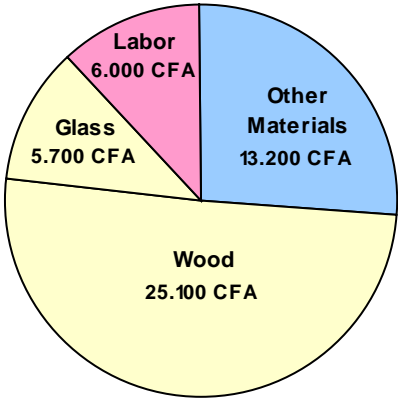


Figure 3: Cost Breakdown

Compounding many of Senegal’s other challenges, plastic waste abounds in its public places. Many products are now packaged in plastic and littering is culturally endemic. Trashcans are a rarity and where they do exist, trash collection services are overburdened. Recovering wasted plastic as a raw material was another incentive to redesign Touré’s oven.

PROJECT DESCRIPTION: OVEN REDESIGN

Creating a new generation of solar ovens for Senegal was a complicated process that demanded careful coordination of parties and resources throughout the summer. As shown in Table 1, additional activities placed extra demands on our team, especially at the end of the summer as we worked to bring closure to our design and analysis.

Actual Timeline															
Month	June				July				August				September		
Dates	7	14	21	28	5	12	19	26	2	9	16	23	30	4	7
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	11	18	25	2	9	16	23	30	6	13	20	27	3	6	30
<u>Oven Redesign</u>															
Travel and Orientation															
Team Building and Research															
Nutritional Study in Louly															
Brainstorm Sessions															
Detailed Design of New Oven															
Production of Molds															
Assembly of First Prototype															
<u>Analysis</u>															
Testing of Current Oven															
Testing of Insulation Materials															
Testing of First Prototype															
<u>Additional Activities</u>															
Rainwater Collection System Design															
Rainwater Collection System Installation															
Reflector Design for TransTech															
Final Presentation in Dakar															
Final Report preparation															

Table 1: Actual Timeline

Project costs totaled approximately \$1531, exceeding our planned budget (Appendix B.3) by 12%. Although CRESA's accounting department managed the distribution of funds through reimbursements and cash advances, the original source of funding was provided by American donations that were secured on behalf of ESW prior to our arrival in Senegal.

Team Building

The crucial step in insuring the success of the project was defining a team of partners that could self-manage the project after we finished our term in Senegal. Beyond the creation of an oven, our most important accomplishment was setting a precedent for how members of Senegalese non-profit, academic, and industrial communities can cooperate on future

development projects. Although we knew the general nature of our work before departing the United States, it took several weeks to understand local capacities and priorities.

First, we met with Abdoulaye Touré to review his existing solar oven design and understand how our skills could best match his technical needs. CRESP then arranged a meeting for us with Professor Paul Malou of the Mechanical Engineering Department at the Université Cheikh Anta Diop de Dakar Ecole Supérieure Polytechnique (ESP). He immediately recommended as partners Alkassoum Anne, a student who oversees the machine shop, and Samba Sy, the director of the fabrication studio. University participation steadily increased as Vincent Sambou, an instructor who runs the Centre International de Formation et de Recherche en Energie Solaire (CIFRES), recruited staff from the Mechanical and Electrical Engineering departments, the Centre International de Formation et de Recherche en Energie Solaire (CIFRES), and the Laboratoire d’Énergétique Appliquée (LEA) who provided substantial technical assistance and generously shared their IT resources, machine tools, and material testing facilities.

After securing commitments from ESP, we followed university leads to contact TransTech Industries, a company based in Dakar that specializes in producing large, hollow products from recycled plastic. The general director of TransTech, Eric Giradon, expressed immediate interest, hoping that our work on new solar oven reflectors could also be applied to TransTech’s plans of commercializing roof-top solar water heaters.

Contact information for all project partners can be found in Appendix B.2.

Establishing Design Requirements

In our very first meeting, Abdoulaye Touré identified cost reduction as his highest priority. He showed us a folding, portable oven (Figure 5), produced in the United States for emergency use and disaster relief. It is made from a



Figure 5: Emergency Solar Oven

corrugated plastic resembling that shown in Figure 4. Using this material in a new design would offer an order of magnitude reduction in cost over Touré’s existing oven designs, but he believed that the pressures of Senegalese customs officials would make importing such a material virtually impossible. We began searching for a locally available corrugated



Figure 4: Corrugated Plastic

material to replace the reflectors in Touré's existing oven design. Although we identified numerous injection molders, blow molders, and even a fiberglass molder, we were unable to find local capacity for extruding corrugated plastic sheets. We abandoned this search following our introduction to TransTech. It was immediately obvious that TransTech's use of recycled plastic in roto-molding large parts was an excellent match for Touré's oven needs.

At the same time, we developed a better understanding of the requirements imposed by Senegalese culture, cooking style, geography, and weather. We spoke to people who prepared meals in our host families as well as with women who use solar ovens in the towns of Yoff and Méckhé. Additionally, we assisted in a nutritional study in the village of Louly Ngokom to better understand the differences between rural and urban cooking requirements.

This user research identified several design requirements for solar ovens in Senegal. Solar cookers represent a major investment for Senegalese families and they should be durable enough to withstand years of rough use in Senegal's concentrated rainfall, unpredictable winds, periodic sandstorms, and harsh sunlight. Conveniently, Senegal's most intense sun comes in the middle of the day, directly prior to the traditional Senegalese lunchtime of 14:00. Although incapable of certain frying steps, we verified that Touré's ovens are able to cook a delicious but modified version of Thiebou Djen, Senegal's national rice and fish dish. Considering that this food is normally prepared for families of 12 or more people at a time, we agreed with Touré's existing requirement of the oven holding up to two 10-liter, legless, cast-aluminum pots of the kind commonly available in Senegalese markets. We also agreed that the best months for solar cooking are between February and November. Since the second-generation oven has received excellent user feedback, it was clear that any new oven design should match or surpass the existing oven in terms of maximum temperature, ease of use, and average cooking times.

With a better understanding of local manufacturing capabilities and an increased familiarity with Senegalese food preparation techniques, we more clearly defined our scope:

How can recycled plastic improve the cost, weight, durability, and/or performance of solar ovens for Senegalese communities?

Using this query, we next organized two large brainstorm sessions with our university partners, a representative from TransTech, representatives from CRESP, and us, the ESW volunteers. We included diverse backgrounds, realizing that the most innovative solutions were unlikely to result from a room of exclusively engineers. Figure 6 shows picture of one of the sessions that produced numerous creative strategies for orienting the stove, improving

portability, and using alternative materials to reduce cost. By the end of the second session, CRES P’s conference room wall was filled with sketches of new ideas.



Figure 6: Brainstorming Session

Initial Calculations

Before starting the design process, we first performed a few basic calculations to determine the ideal incline angle of the windowpanes. The altitude of the sun, the angle from the horizontal plane, varies throughout the day and throughout the year. In Senegal, the sun is at its highest point in the sky, the maximum altitude, at 13:00 each day. A plot of the maximum sun angle at 13:00 as a function of month can be seen in Figure 7. The angles shown on the graph are the complements to the altitude, the angle from a perpendicular line to the horizon. As the earth revolves around the sun, the daily maximum altitude changes, highest in the summer months and lowest in winter, as can be seen on the graph. User feedback indicated that the oven would see limited use from mid-November to mid-January, due to increased cloud cover during those months, illustrated by the gray section on the graph.

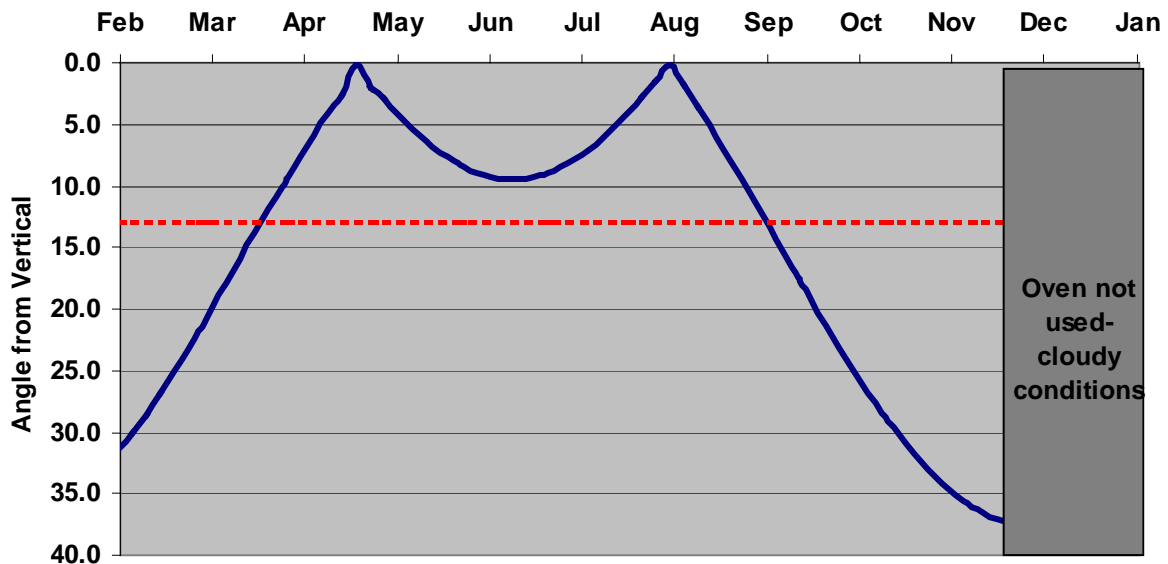


Figure 7: Sun Altitude at 13:00

The windows should be at an angle to maximize the amount of solar radiation entering the oven box, thus they should be perpendicular to the rays' direction. We used the data presented in the graph to calculate the ideal angle of the windows. The average of sun altitudes at 13:00 was taken from the months of February to November and we calculated an ideal incline angle of 13° . The calculation is shown in Appendix C.1. The position of the second-generation oven is designed to be adjusted every half hour, to track the movement of the sun. It favors east in the morning and west in the afternoon. Although similar repositioning improves the performance of the third-generation design, its pair of reflectors works together to direct sunlight into the cooking box even if it is left facing generally southward or northward, with the sun traversing a path along its long axis.

We also calculated the reflectors' range of motion necessary to accommodate the variety of sun positions throughout the day and throughout the oven's season of operation. Specifically, the back reflector must open a minimum of 90° from the window frame and have 39° of additional motion to perform best when the sun is directly overhead, as shown in Figure 8. The front reflector must swing open 112° for overhead sunlight and an additional 38° for the early-day sun of mid-January. These angles ensure that almost all the sunlight between 10:00 and 15:00 during the sunny season will be reflected into the oven. Detailed calculations are presented in Appendix C.1. To allow good adjustment technique, the reflectors must be capable of being set almost anywhere in these ranges. If discrete position settings are unavoidable, the steps between positions must be as fine as possible.

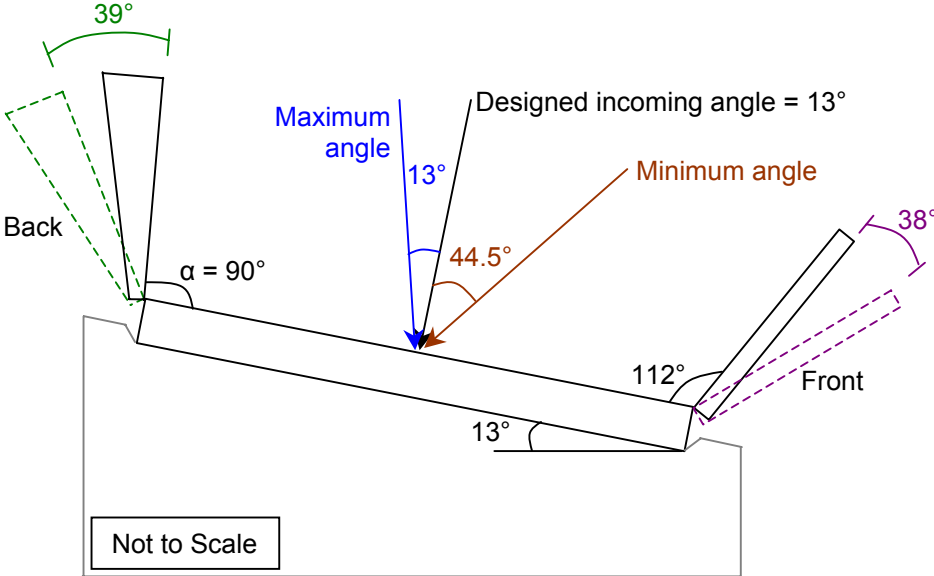


Figure 8: Minimum Acceptable Range of Reflector Motion

Description of New Design

After the calculation of the incline angle, we shifted focus to the broader design challenges of a new solar oven. Based on Abdoulaye Touré's two previous models, this third-generation oven was specifically designed for the unique conditions of rural West Africa. It allows for increased durability, performance, and portability at a significantly reduced capital cost. This was accomplished through new product architecture, widespread use of recycled materials, and the addition of new features. Beyond its technical achievements, the design's most important success is that Senegalese workers can produce it in Senegal with Senegalese materials for Senegalese communities.

Product Architecture

Our team's design is largely a hybrid of basic systems found in other solar cookers. Similar to most contemporary box-type ovens, our design includes an insulated box with a transparent lid through which solar radiation can enter. However, it also borrows from parabolic cookers, employing reflectors to intercept and

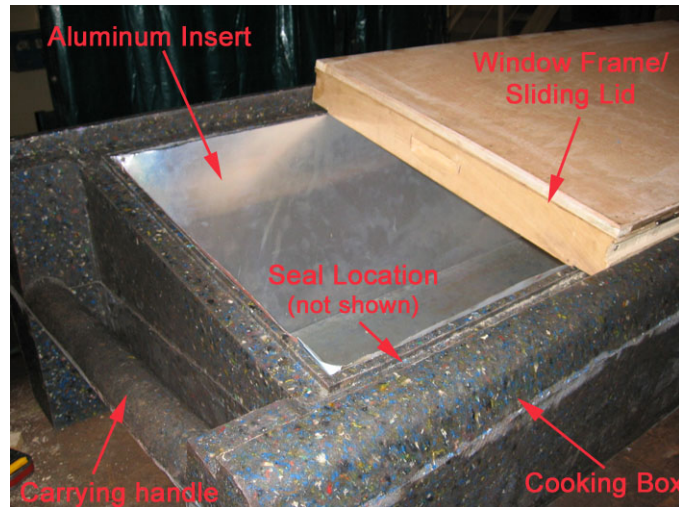


Figure 9: Cooking Box Components

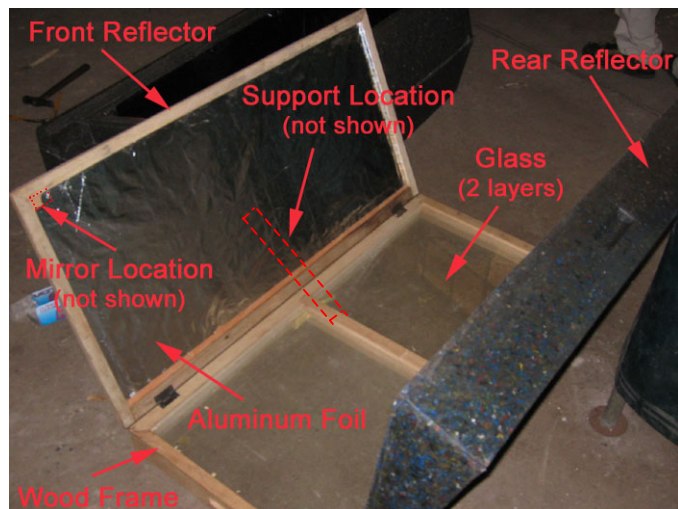


Figure 10: Window Frame and Reflector Components

redirect additional energy towards the cooking vessel. Like Touré's previous ovens, the new design remains close to ground level and has two cooking stations. Improved usability comes from a recombination of its basic components: the reflectors, the cooking box, and the window frame assembly. Component descriptions are shown in Figures 9 and 10 and the assembly hierarchy is described in Appendix C.5.

Molded Construction

Instead of being assembled from numerous, individually prepared pieces, most of the geometric features of the cooking box and rear reflector are produced in one step through

roto-molding. For example, an array of adjustment holes can be molded along the middle of the reflectors, eliminating the need for complicated post-process drilling. The molded parts can be produced in large-quantity serial production runs, independent from other components, and without the need for custom-fit assembly procedures.

Pairs of molds, which are fabricated from welded sheet steel, determine the parts' exterior surfaces. This ensures a high degree of consistency for many of the oven's critical-to-function dimensions. For example, the molds directly control the rails on which the window frame slides and the surfaces to which the aluminum interior attaches. Both are locations where consistent dimensions are critical.

Sliding Access

The sliding lid in our new design represents a departure from Touré's previous oven architecture. In the past, the transparent cover hinged open like a door to allow access to the cooking stations. We noticed a strong cultural tendency in all styles of Senegalese cooking to frequently check the food to see if it is done. Unfortunately, this results in a substantial loss of heat inside the oven. Operating more like a drawer, our sliding lid allows each cooking station to be accessed independently, not requiring that the oven be completely opened to the ambient air. This arrangement places less torsional stress on the window frame and does not require the cooking box to withstand the focused loads of hinges and end-of-travel tethers.

Double Reflectors

This design employs two flat, adjustable reflectors to capture solar radiation and redirect it into the oven's interior. They pivot on the long sides of the frame that supports the glass panes and slide with the frame when the oven is opened. The second reflector doubles the oven's solar gathering capacity and provides an added degree of protection against stray, glass-breaking children's toys.

Better Materials

The most important factor in reducing the total oven cost is reducing the cost of materials. The ecologically preferable principles of reducing, reusing, and recycling make good economic sense. We considered them in the specification of every material in our new design.

Recycled Plastic

In our new design, many of the components are made from recycled plastic. The exterior of the cooking box and rear reflector result from a rotational molding process, commonly called roto-molding. The front reflector is press molded, and the frame that supports the glass panes can be fabricated from TransTech's plastic wood. Besides adding new value to the plastic that litters many Senegalese communities, TransTech's process

promotes the long-term advantages of using plastic, instead of wood, in often-harsh outdoor weather of West Africa. More resistant to moisture and fire, plastic reduces the already excessive demand for wood.

Originally developed for its wastewater tanks, TransTech has a network of suppliers throughout Senegal that gather empty bottles, plastic bags, and other waste streams of plastic. This material is brought to centralized processing locations, chopped, and purportedly cleaned before being packaged in bags similar to those widely used in Senegal for 50 kg portions of rice. They are then delivered via truck to TransTech's production facility in Dakar. Although most bags were labeled as coming from Kaolack, TransTech claims to have multiple sources. Beyond its inherent heterogeneity, we expect that the composition of this mixed, chopped plastic further varies throughout the year and depends on the region of collection.

In our roto-molded and press molded parts, recycled plastic is combined with polyethylene (PE) resin at a ratio of approximately four to one. Although much of the recycled plastic approaches a liquid state during molding, the PE acts as a binder, holding the pieces of recycled plastic together, filling voids between the pieces, and providing a uniform surface finish. TransTech typically imports its PE resin from a supplier in Houston, Texas and in the United States the production of resin from recycled PE is a well-established technology. Therefore, we believe that in this new design all of the plastic components can be made entirely from post-consumer material.

Although TransTech has encountered no problems using recycled materials in products that substantially interact with food preparation such as roto-molded picnic tables and plastic-wood surfaces for fish rendering, they told us that Senegalese law prohibits the use of recycled plastics in products that are intended for the storage of drinking water. Our new design involves no contact interaction between the recycled plastic and the prepared food.

Recycled Aluminum

The interior of the new oven is designed to recycle the aluminum printing plates used in Senegal's printing industry. This material is approximately 0.6 mm thick and is available in various sheet sizes. Although we have specified a pattern for cutting and folding the aluminum (Appendix C.4) we expect this shape may evolve as Touré experiments with various strategies for attaching and supporting the aluminum in the cooking box. Prior to our departure, Société Africaine d'Impression Industrielle (SAII), a major printer in Dakar, agreed to directly supply Touré with the sheets necessary for our new oven design. After fabrication, the interior of the aluminum is brushed with black acrylic paint, which is widely available around Dakar.

Reflective Film

Although better materials may now be available, our current design specifies the lamination of common aluminum foil on the two reflecting surfaces. Unfortunately, the foil is not terribly durable, but it seemed to be sufficiently reflective and widely available in Senegal. One possible alternative to aluminum foil is a metalized plastic film that is used for the packaging of food items such as powdered milk in Senegal. This material has high reflectivity, and is much stronger and durable than traditional foil.

Insulation Materials

Due to time constraints, our prototype uses fiberglass insulation. However, this oven is designed to use loosely packed, locally available material. Because most materials have a tendency to settle during initial use, we recommend that in production units, a hole be placed in the plastic box to allow insulation to be poured in after the aluminum interior is installed. This would allow for complete filling of the insulation cavity. This hole could then be closed with melted plastic.

Double Glazing

Our oven design uses four 3 mm thick, 50 cm square panes of glass. Prior to the frame's final assembly these replaceable panes are installed in parallel dadoes along the inside of the window frame rails. The double panes help trap in the heat and insulate the oven's cooking chamber from ambient temperatures. The 50 cm by 50 cm pieces can be cut from the glass sheets most commonly imported to Senegal with little waste and this size is a loosely accepted standard used in many contemporary solar cookers. Unfortunately, the glass panes remain fragile and relatively expensive.

Lid Seal

The seal material is an important factor in oven performance. Because the plastic cooking box and window frame will likely exhibit some warping, the gap between them must be sealed with a highly conformal material. The material must be soft enough to easily compress at tight spots but still return to its original thickness after prolonged exposure to heat. At the time of this report's preparation, a search for a suitable material has not been completed. The foam material commonly used in Senegalese mattresses and a type of blue, pliable, plastic packaging material offer possible solutions. Ideally, the seal material can be recovered from the waste stream of processes that pre-exists in Senegal.

New Features

Flat Bottom

From our observations that sunny, solid, level surfaces are often unavailable in Senegal, our new design eliminates discrete legs. Instead, the broad, flat bottom is intended to rest stably on sandy ground.

Carrying Handles

The design's molded handles are intended to simplify the transportation of the oven around Senegalese compounds. Their diameter, approximately 50 mm, is intended to fit comfortably in the hands of users while still providing a durable, convenient lashing point for hauling the oven greater distances.

User Interfaces

The depressions located at the ends of window frame and at the outer edge of the rear reflector are easily recognizable points of user interface. The handholds on the window frame provoke an intuitive sliding motion, helping novice users to correctly access the oven's interior.

Improved Reflector Adjustability

Like Touré's previous designs, the reflectors can be propped open to various angles by placing a strut between holes along the middle of their reflecting surfaces and pockets in the middle rail of the window frame. At the time of this report's publication, a system for securing the reflectors had not yet been installed on the prototype, but we propose that the reflectors be secured firmly against the adjustment struts by tensioning a common cord that runs between the midpoints of their free edges. The new design specifies a much finer array of adjustment holes than the previous model and a new hinge arrangement (see Appendix C.4) allows the reflectors a full range of movement so that they can be adjusted for extreme sun positions (see Figure 8).

Similar to Touré's second-generation oven, the new prototype has small mirrors in the corners of the reflectors to aid in orientation. The oven is correctly oriented and the reflectors properly adjusted when these mirrors cast spots of sunlight on the opposite corners of the window frame.

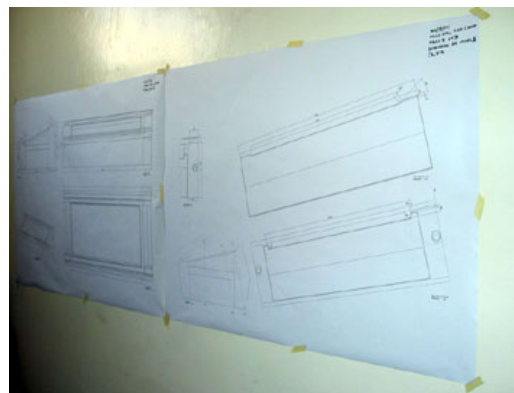


Figure 11: A0 Design Drawings

Prototype Fabrication

After the preliminary design process, the components were then modeled in a three-dimensional computer-aided design (CAD) program, Catia V5, and large, A0 size drawings of the box design, as seen in Figure 11, were printed and given to TransTech to make the mold for the cooking box. In one long weekend, Alkassoum Anne, Samba Sy, two workers from TransTech Industries, and Francis built the mold at ESP, Figure 12. In parallel with the mold construction, tests were run to characterize the performance of the existing oven along with material property tests on potential insulation materials. A final presentation summarizing our work over the summer was given a couple days before our scheduled departure, to an audience that included ESP, TransTech, and CRESP representatives. A picture from the presentation can be seen in Figure 13.



Figure 12: Mold Construction



Figure 13: Presentation

Following the presentation and completion of the critical-to-function mold features, Francis left as planned on August 20th. However, Robin rescheduled her flight and stayed in Senegal an additional two and a half weeks help complete the prototype. The first box was produced from the mold the following week, as seen in Figure 14. Shortly after, Alkassoum Anne, Samba Sy, and

TransTech workers built the mold for the roto-molded, rear reflector and the first reflector was produced. Touré purchased the additional materials for the prototype, the team assembled the oven, and Vincent and Robin tested the prototype on September 6th. The actual duration of this entire process differed from our proposed timetable, which can be found in Appendix B.1.



Figure 14: Production of First Oven Box

Due to time constraints, the design was modified slightly to expedite and simplify the assembly of the first prototype. First, TransTech’s machine for manufacturing the pressed reflector was not functioning at the time, so the front reflector was instead constructed from a piece of plywood. Second, our characterization experiments showed that the temperature of the window frame stays within the performance limits of TransTech’s recycled plastic wood material and can thus be fabricated from such a material, but the prototype uses conventional wood. Finally, for ease of construction and due to incomplete results from the insulation tests, standard fiberglass building insulation was used for the prototype. In commercialized ovens, this insulation would be some abundant local product, such as sawdust, rice hulls, or peanut shells. The major components of the first prototype were assembled by September 6th, the day that Robin left Senegal. It can be seen in Figure 15.



Figure 15: First Prototype of New Solar Oven

PROJECT DESCRIPTION: ANALYSIS

Temperature Experiments

In addition to designing the new solar oven, we conducted two experiments, one to characterize the performance of the existing second-generation oven and the other to determine the properties of potential insulation materials. First, we wanted to determine the maximum temperature at certain locations in the oven during operation. This information was useful in designing the new prototype, to insure that the plastic components would not be in danger of melting.

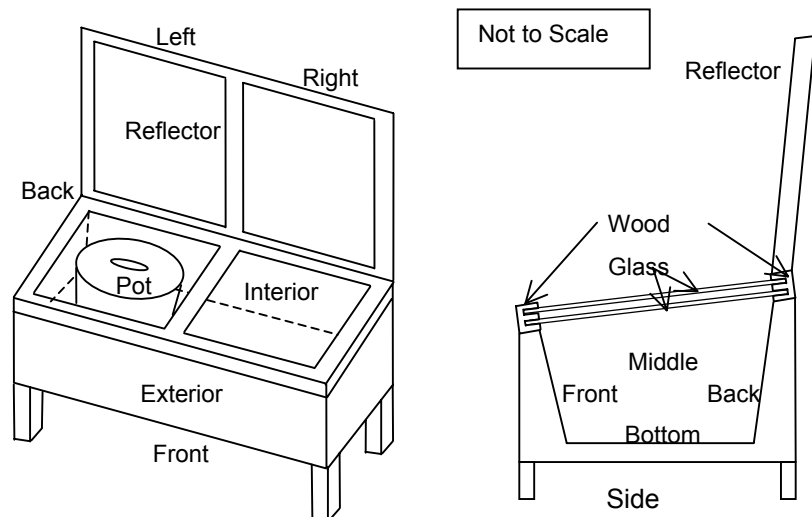


Figure 16: Solar Oven Location Descriptions

We put thermocouples in ten different locations in the oven, described in Figures 16 and

Table 2, and tested the oven from 10:00 to 15:00, the time period when the oven is primarily used. The thermocouples were connected to an Agilent 34970A Data Acquisition/Switch Unit. The temperatures were taken every five minutes using Agilent Benchlink Data Logger software. A typical graph of the temperature in the interior of the oven, the water temperature, and the ambient temperature between these times is shown in Appendix C.2.

As suggested in a report prepared by a team of ESW students from Cornell University, we followed the American Society of Agricultural Engineers (ASAE) Standard X580, given in Appendix C.6, to calculate the standard power for the oven. This involved placing a pot of water in the oven, the volume of which is calculated based on the solar intercept area of the oven. For the original oven, the amount of water necessary for the test was 5 liters. The oven is operated from the solar time of 10:00 to 14:00, corresponding to 11:00 to 15:00 local time in Senegal. Adjustments were made to the orientation of the oven and reflector every half hour, to ensure the maximum amount of solar radiation was entering the oven. The temperature of the water and the ambient temperature were taken every five minutes and this data, along with the incoming solar insolation for the same time period, and were used to calculate the standard power of the oven, according to the formulas given in the standard. Using data taken over two days, we calculated the power of the oven to be approximately 19 Watts for a difference between the water temperature and ambient temperature of 50°C. This power rating can be used to compare the performance of this oven with both the new version and to other solar ovens around the world. We performed the same test and calculation with the new oven prototype. However, due to time limitations, the prototype was not completely finished and was tested without the seal and reflector supports in place. Thus the actual performance of the new oven should actually be better than these preliminary results. Despite these missing components, the standard power of the new oven at a temperature differential of 50°C was calculated to be 28 Watts, which is higher than that of the old model. A more detailed description of the analysis and additional data from the experiments are in Appendix C.2.

T1	n/a
T2	Interior left, front
T3	Between glass, front right
T4	n/a
T5	Interior right, middle
T6	Interior right, bottom
T7	Interior left, back
T8	Water Temperature
T9	Exterior, front left
T10	Outside pot cover
T11	n/a
T12	n/a
T13	Ambient
T14	n/a

Table 2: Thermocouple Locations

Insulation Material Testing

Insulation is an important component of the oven. It is used to fill the empty space between the aluminum insert and the recycled plastic box. Good insulation materials will allow little heat transfer from the insert to the surrounding area, trapping heat in the cooking area. The availability and price of insulation materials varies with location. We set out to determine the conductivity and diffusivity of common insulation materials to allow the assemblers to decide what would be the best material to use based on local availability and price. The materials we chose to test were mainly items that are readily abundant in Senegal and are usually discarded: coconut husks, cotton fiber, fabric scraps, filao leaves, foam, old newspaper, new peanut shells, partially-decomposed peanut shells, rice hulls, sawdust, wood shavings, and waste plastic pieces. All these samples, with the exception of the foam were free of charge. However for mass production, some cost might be associated with procuring these materials in larger quantities.

The first experiment we ran was to determine the thermal conductivity of the materials. Thermal conductivity is a physical property that characterizes the material's ability to transfer heat. Small thermal conductivities indicate a poor heat conductor or a good insulator. The Laboratoire d'Énergétique Appliquée (LEA) at the university already had an experimental set-up for conductivity and diffusivity tests, as shown in Figure 17. We fabricated a box to hold the samples during the test, which consisted of two thin aluminum



Figure 17: Material Testing Set-Up

plates separated at their edges by a poor conductor, styrofoam. Two temperature sensors were attached to the box, one on each plate. The box was then placed inside a larger insulated box, as shown in Figure 18. Cold air was pumped across the bottom side of the sample, where the

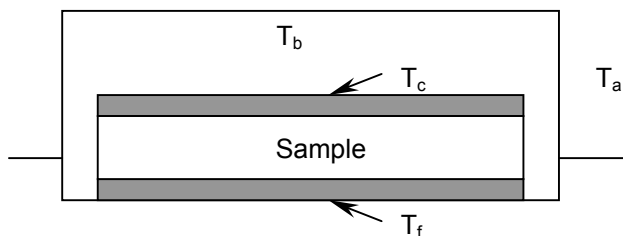


Figure 18: Experimental Set-Up

sensor T_f was connected. The interior of the larger insulated box was heated by a resistive sheet and also contained a temperature sensor, T_b , which measured the air temperature. There was an additional sensor separate from the apparatus to measure the ambient temperature, T_a . Another sensor, T_c , was connected to the top plate. We controlled the

voltage to the resistor, varying it until the temperature between T_b and T_a was less than 1°C and the temperature difference between T_c and T_f was constant. Using this information, the conductivity could be calculated. Further explanation and data are in Appendix C.3. We ran two experiments for each material, to verify the accuracy of the tests.

After the conductivity tests were finished, we tested the diffusivity of the materials. Thermal diffusivity is a measure of the way heat flows through a material. Materials with high diffusivities will rapidly adjust their temperature to the surroundings, so a low diffusivity material is desired for a good insulator. The same experimental set-up was used, with a few modifications. The box used was similar with two thin aluminum plates joined with plexi-glass instead of styrofoam. Only one temperature sensor was used, T_c , attached to the top of the box. For the experiment, a flash of light heats the bottom plate for 30 seconds and the temperature of the top plate is recorded. The temperature rises as the heat transfers through the material and the temperature and time information is used to calculate the diffusivity. Additional information about the diffusivity experiments can be found in Appendix C.3.

The conductivity and diffusivity results are shown graphically in Figure 19 and in tabular form in Appendix C.3. From conductivity alone, nine materials seem to be better insulators than an empty cavity. Only waste plastic, coconut husks, and decomposed peanut shells had higher conductivities.

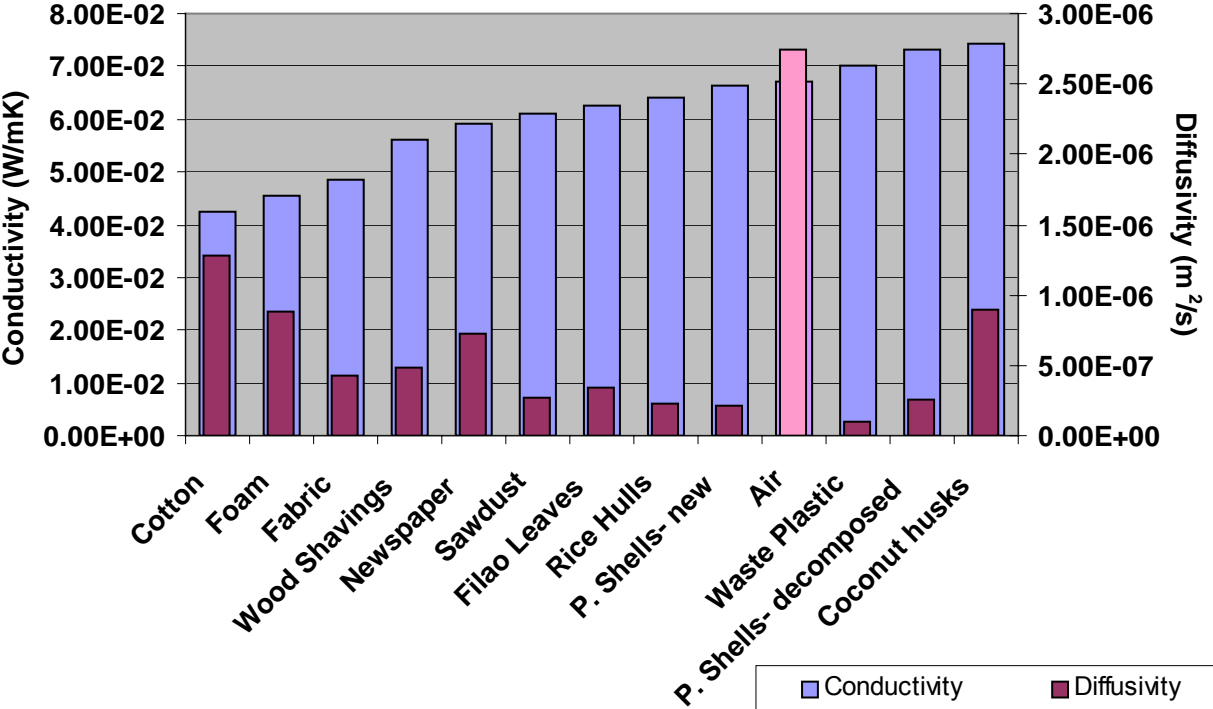


Figure 19: Conductivities and Diffusivities of Insulation Materials

but appear to be correlated with the density. The denser the material, the lower the diffusivity. This plays a role in the selection of the insulation material, since weight is a consideration in the final assembled oven. The materials were ranked according to their conductivity and also ranked separately by their diffusivity, with a lower ranking indicating better insulation properties. These individual rankings were then averaged and the materials sorted based on this new rank. Materials with the same average ranking were further sorted by their densities, with lower density materials given higher priority. The resulting list is in Table 3, with the first material, fabric scraps, as the best insulator.

Material	Average Rank
Fabric Scraps	5 (best insulator)
Rice Hulls	5.5
Sawdust	5.5
Peanut Shells- new	5.5
Foam	6
Wood Shavings	6
Waste Plastic Pieces	6
Cotton Fibers	6.5
Filao Leaves	6.5
Newspaper	7
Peanut Shells- partially decomposed	8
Air	11.5
Coconut Husks	12 (worst)

Table 3: List of Insulators, Best to Worst

PROJECT DESCRIPTION: ADDITIONAL PROJECTS

In addition to the design and fabrication of the solar oven, we completed two other engineering projects during our time in Senegal. The first was the design of a rainwater collection system for CRESP and the second was a preliminary model for TransTech Industries, to help determine the ideal reflector shape for their solar water heater.

Rainwater Collection System

Prior to our arrival, the Global EcoVillage Network, based in Denmark, delivered a crate containing a 250-liter tank and an assortment of components for a rainwater collection system to CRESP. CRESP hoped to test the feasibility of collecting rainwater from Senegal’s traditionally flat rooftops and requested that we design and install a system at the CRESP headquarters in Yoff before the season’s first rainfall. CRESP was especially interested to see if this system could help provide water for its demonstration permaculture garden.



Figure 20: Rainwater Collection Tank (left) and Piping System (right)

The system we designed and installed is shown in Figure 20. Our design considerations and further technical information is available in Appendix D. The system's tank completely filled after one rain shower, verifying the technical feasibility of flat roof collection. At the time of our departure, CRESP was interested in expanding the capacity of the system to carry more of their garden's watering load during and after the rainy season.

TransTech Model

As previously stated, TransTech is interested in designing a rooftop solar water heater. Giradon's proposed design consists of a large, 1000-liter rooftop water storage tank, containing a smaller 200-liter tank inside. This smaller tank will be located at the top of the larger tank and heated by solar radiation to provide households with warm water during the winter months. Ideally, the water will be heated to approximately 60°C during the day and the temperature will not drop more than 20°C during the night. This will allow people to take warm showers in the morning during the cooler months. Giradon proposed that our reflector design could also be used for his rooftop solar water heater. Based on this possible collaboration, he generously offered to produce a recycled plastic prototype of an entire solar oven.

For the model, we first calculated the ideal incline angle for the surface of the tank and the ideal orientation of the reflectors to maximize the amount of intercepted solar radiation. We then wrote a MatLab program to determine the best two-dimensional reflector

shape and started a simple three-dimensional model. We were unable to finish the analysis due to time limitations. A copy of the report submitted to TransTech is in Appendix E. It documents the work we accomplished, modeling details, and proposed future work.

CONCLUSIONS AND RECOMMENDATIONS

This summer we participated in a unique partnership between the non-profit, academic, and industrial sectors to design and fabricate a new generation of solar ovens for Senegal. The new solar oven addresses several problems by replacing the expensive wood components with recycled plastic and incorporating more user-friendly features. Preliminary tests show the first prototype is more powerful than the older generation oven. A low-cost, efficient solar oven has significant benefits for Senegal and surrounding West African countries. Many environmental problems can be mitigated through the use of these ovens. At the time of this report, TransTech estimated the cost of the recycled plastic components to be approximately 50,000 CFA. This is higher than we anticipated, but we think the cost can be reduced to 30,000 CFA once mass production is started.

Future Work

There is still much work to be done before the oven can be widely distributed. ESW's ability to supply CRESP with one or two volunteers this winter (2005) is the single most important step in stabilizing the future of solar cooking in Senegal. The immediate concern is finishing the first prototype and commercializing the design for use in an upcoming Global Environmental Fund demonstration project with a women's group in the ecovillage of Méckhé. Funding exists for up to 100 units, but CRESP has neither the technical staff nor resources to meet this immediate deadline. Securing another ESW intern to act as a coordinator between the different parties, Abdoulaye Touré, the university, CRESP, and TransTech, is a top priority at the time of this report. With such a person in place, the production and distribution of the solar oven should be able to proceed as planned.

After this is completed, modifications can be made to the design and components of the oven to optimize performance, assembly process, and user interface. In parallel, a model for production, assembly, and distribution must be clarified. We envision that the components of the ovens, including the box, reflectors, and glass, will be manufactured in Dakar. These items can then be transported to regional centers where the oven will be assembled with local materials and labor.

A longer term future goal is to set up a mobile plastic recycling program. According to some established, periodic, perhaps monthly, schedule, individuals could bring plastic litter to a public place and exchange it for a recycled plastic product, such as a chair, bucket, or even a solar oven. Hopefully seeing the waste transformed into a useful product will provide participants an incentive to collect and save their plastic waste.

Once the manufacturing process is established in Senegal, the oven design and its manufacturing model can be re-created elsewhere. There is interest in developing different models of the oven. For example, commercial-sized ovens show potential merit as well as food dryers. These kinds of ovens would move beyond the domestic realm and be purpose-built, enterprise catalysts. Francis intends to consider the business case and technical requirements of mango drying during his Autumn 2004 Masters coursework at Cambridge University.

Partnership Roles

In retrospect, our staggered departures allowed the African team members to develop more project responsibility and a greater sense of project ownership before completely losing touch with us American volunteers. Engineering our own obsolescence was one of the most challenging parts of the project and although we were able to design arrangements that promoted continued involvement on behalf of all the partners, it may have been disastrous if both of us had left at once.

At this stage, the partners will play a variety of roles in the continuation of the project. CRESP and Abdoulaye Touré will handle distribution of the ovens, promotion of the oven throughout Senegal and surrounding countries, as well as coordinating the transport and local assembly of the ovens. Touré currently runs weeklong seminars in Senegalese villages to educate and train villagers on how to assemble and use the ovens. This program will be continued with the new generation of ovens. CRESP is a member of several global environmental and EcoVillage organizations and will publicize the new oven through these channels. The partners at ESP will be responsible for redesigning and modifying the oven design as is necessary. Additionally, they will run further tests to characterize the performance of the oven. We believe that TransTech has sufficient incentive to streamline their molding process oven in order to fully meet our discussed price points.

Future work can be conducted by ESP graduate students for their dissertation and thesis requirements. In addition to continuing the performance and power tests, students can continue the insulation material testing, verify the conductivity and diffusivity results along

with running other material property tests. Tests can be run on the reflectivity of different materials to determine which is the most cost efficient and effective material to use for the reflectors. Finally, students can make modifications to the oven, such as using different insulation materials, varying the reflector configuration, eliminating reflectors, and changing the orientation of the oven to characterize how these changes affect performance.

Social Considerations

There are still a few problems to be addressed before the solar ovens are widely used and accepted throughout Senegal. First, even though the cost of the oven should be reduced, it is still a significant investment for most people. Ideally some type of micro-credit program needs to be set up to help villagers purchase the ovens. They need to be made aware of the long-term savings they will have with the solar oven, since firewood and gas will not need to be purchased to operate the oven.

Second, cultural acceptance is a continuing, though surmountable, challenge, as solar ovens would demand some change in Senegalese cooking and eating habits. Senegal's national rice and fish dish, Thiebou Djen, cannot be made in the oven because it traditionally requires a frying step. Instead, Touré's family of ovens is suitable for a baked version that presents a much healthier alternative. These culinary adaptations should remain a main theme of Touré's training programs and CRESA must continue its support of adapting other Senegalese recipes and nutritional practices, such as water pasteurization and preparation of baby formula. This complements a broader movement that is currently occurring in Senegal, where local nutritionists and the global ecovillage network are promoting a cultural shift towards healthier cooking and eating habits.

Widespread Interest

The development of this new solar oven has also generated widespread interest beyond Senegal. The Mauritanian government has asked Touré to send them weekly reports on the status of the project. Mauritania is possibly an even better fit than Senegal, since wood is scarcer and family sizes are smaller. As long as the ovens are easily transportable by camel, most experts predict widespread acceptance. Additionally, people in Europe and Asia have contacted Touré, inquiring about the new ovens.

APPENDIX A: PERSONAL REFLECTIONS

A.1 Robin's Reflections

Going into this summer I had no idea what to expect. Our circumstances were also unique, as we were re-staffed on this Senegal project four days before our departure, after our original project in Nigeria fell through. The experience and work we accomplished this summer far exceeded anything I could have imagined. I think we were very lucky at the way things worked out. We had a clearly defined project going into Senegal, with a partner, Abdoulaye Touré, identified. Touré has been promoting solar ovens throughout West Africa for almost 20 years and had a clear idea of what needed to be done to further the cause. Once we arrived in Senegal, it was clear what our goal was for the summer, reduce the cost of the oven. We formed partnerships with people at the university (ESP) and through them, we partnered with TransTech. Everyone we worked with was fully dedicated to the project and put in a lot of time and effort to ensure a successful outcome. We couldn't have asked for a better team.

Another great thing about the project is that we got to participate in all aspects of it, from the original design, project management, manufacturing, to the final assembly of the prototype. We were fully involved in every step. Due to the nature of our project, we got to see and experience a wide variety of things. We were always running around to different parts of Dakar, purchasing materials, visiting factories, and even trying to find chicken feathers in a huge rainstorm. We got to work closely with people at the university, running experiments that we designed, and with people from industry, which gave a different perspective to the process. Also because of the nature of CRESP, with its wide variety of projects, we got to participate in other projects. We were part of a team that went and did a baseline survey in Louly, a village a couple hours south of Dakar. Living in the village and meeting the villagers during our week stay was a worthwhile experience. We were also recruited by CRESP to design and install a rainwater collection system. Additionally, we did a little computer modeling for TransTech for their solar water heating system.

Of course as with any project there were setbacks. A large number of these were due to the cultural differences of the way work is done between the US and Senegal. Everything ran on a much slower time scale, "African time", as we called it. Meetings that we expected to run for an hour usually took three to four hours. The initial brainstorming session we held went a couple hours longer than we planned and we didn't even cover half of the topics we had planned. We had to schedule an additional session to cover the remaining issues. There

were a few other similar incidents, for instance we lost close to two weeks of work time between when we gave the oven box plans to TransTech and when the work on the mold began. This ended up pushing the timing of the project back and the prototype was not completed by our originally scheduled departure date.

I ended up staying an additional two and a half weeks in Senegal to oversee the prototype construction. This additional time turned out to be very worthwhile. Everyone worked very hard to make sure the first prototype was completed by the day of my departure and we even had time to run one test of the new oven on the day I left. Another good thing that occurred during that time is that it allowed the project to be successfully transitioned from us foreigners having key roles in the project and making many of the decisions, to the Senegalese running the project. I noticed during my last two weeks in Senegal, the local partners took a much greater role in decision making and discussing the continuation of the project after my departure.

All that said, this summer has been an amazing experience engineering wise and living in a developing country. I feel that staying with a host family was the perfect way to experience and understand the culture of Senegal. Everyone was very friendly and helpful. I do wish that I knew how to speak a bit of French before I went. It made things very difficult not being able to speak French and we constantly had to rely on having a translator. It was better at the end, after taking French classes and interacting with people for a few months. Learning a few words of Wolof proved to be very helpful, letting people know you were interested in their culture and were trying to fit in.

A.2 Francis's Reflections

My time in Senegal was one of the best summers of my life. The brilliance of my friendships, travels, and personal growth is too great to fully describe, however I can share some lessons that might be generally useful for future ESW volunteers, in particular those who will be working near Dakar.

Since volunteers will not (and probably should not) normally design their own placements, they should be cautious of any scenario that does not address certain concerns. I believe these factors were essential in giving me peace of mind that my work would create more value than harm:

- We conducted our design work in-country, with Senegalese stakeholders.
- The local NGO, not us, identified our project.
- Although still relatively short, we were able to work for at least 10 weeks.
- We partnered with Senegalese peers not only for translation, but also technical tasks
- We had language, IT, accounting, and logistical support from CRESP, a local NGO. Their institutional reputation and stability was essential in doing high quality work.
- We had the ability to access the academic, political, industrial, and commercial resources of the capital city.
- We were not the only foreign intern staff at our location.
- I lived with a fantastic host family that was able to smooth my transition into Senegalese life.

Because of the pitfalls that inevitably characterize development work, I would be hesitant to endorse the unsupervised placement of students who have only a traditional undergraduate engineering training. Engineering that is appropriate for a place like Senegal is more similar to that of the USA than most people might imagine, however Senegalese communities seemed less capable of absorbing the economic and environmental side effects of poor design. My work had to be better than that which I would have done in safety-netted American society.

I was surprised at how difficult it was to fundraise for my placement, but I am grateful that CRESP persuaded us to earmark money specifically for our project expenses. Although relatively small compared to the budgets of traditional aid agencies, our expenses were vital to the execution of the project. In the future, I would recommend, though, that volunteers engage in this kind of work while they have the funding that comes with academic affiliation or as an extension of a professional experience.

In addition to the money administered through ESW (air transportation, housing, vaccination, project expenses, etc.), I spent approximately \$950 out of pocket during my 10-weeks. This included occasional entertainment costs, supplementary food costs, souvenirs,

gifts, a replacement passport, the cost of a three-day layover in Casablanca, and recreational outings with other interns to Ile de Ngor, Ile de Gorée, St. Louis, and The Gambia. Although there is no difficulty using ATM cards in Senegal, it is necessary to exchange all of your West African Francs (CFAs) before leaving Dakar's airport, as there is no international trading of this currency.

My summer was shaped substantially by the remarkable performances of others. My fellow CRESP interns provided constant inspiration and CRESP's Senegalese staff were absolutely brilliant. John Fay offered a refreshing optimism and admirable dedication and Marian Zeitlin was a shining example of selfless commitment. Most importantly, I will be forever indebted to my co-author, Robin, for her patience, professionalism, and eleventh-hour flexibility—her travel savvy and sober realism saved the day more than once. Never before have I worked with a more thorough and complimentary colleague.

My time in Senegal helped me confirm my passion for product design and gave me a glimpse of the regional stability that had long been missing from my nomadic lifestyle. I hope to use Senegalese technical challenges as the basis of my master's dissertation, am continuing to improve my French, and look forward to one day returning to Yoff. It is my sincerest wish that this account might be a stepping-stone for others who will follow in this path. I encourage future volunteers to widely plagiarize this work, exceed our successes, and avoid my mistakes.

APPENDIX B: GENERAL DOCUMENTATION

B.1 Timelines: Proposed and Actual

Proposed Timeline:

Month	July				August		
Dates	5 - 9	12 - 16	19 - 23	26 - 30	2 - 6	9 - 13	16 - 20
Brainstorm Session							
Detailed Design of New Prototype							
Production of Mold by TransTech							
Testing of Current Oven							
Testing of Insulation Materials							
Final Assembly of First Prototype							
Testing of First Prototype							
Design Modification							
Manufacturing of Second Prototype							
Testing of Second Prototype							
Final Report							

Actual Timeline:

Month	June				July				August				September		
Dates	7	14	21	28	5	12	19	26	2	9	16	23	30	4	7
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	11	18	25	2	9	16	23	30	6	13	20	27	3	6	30
<u>Oven Redesign</u>															
Travel and Orientation															
Team Building and Research															
Nutritional Study in Louly															
Brainstorm Sessions															
Detailed Design of New Oven															
Production of Molds															
Assembly of First Prototype															
<u>Analysis</u>															
Testing of Current Oven															
Testing of Insulation Materials															
Testing of First Prototype															
<u>Additional Activities</u>															
Rainwater Collection System Design															
Rainwater Collection System Installation															
Reflector Design for TransTech															
Final Presentation in Dakar															
Final Report preparation															

B.2 Project Contact Information

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B.3 Budget: Proposed and Actual

DESCRIPTION	PROPOSED	ACTUAL	ACTUAL (US)
Brainstorming supplies	20,000 CFA	7,900 CFA	\$15
General transportation	50,000 CFA	104,900 CFA	\$202
Materials for design work	10,000 CFA	6,025 CFA	\$12
Communication costs	15,000 CFA	43,590 CFA	\$84
Meeting materials	20,000 CFA	-----	----
Materials for final report	15,000 CFA	-----	----
Trip to recycling site	60,000 CFA	-----	----
System prototypes	50,000 CFA	56,465 CFA	\$109
Performance tests	30,000 CFA	1,300 CFA	\$3
Occasional meals for partners	20,000 CFA	24,300 CFA	\$47
Mold development costs for prototype	130,000 CFA	203,500 CFA	\$391
Partner/Translator (Anne and Sy)	120,000 CFA	330,000 CFA	\$635
Translator (Mambouye)	18,000 CFA	18,000 CFA	\$35
Extra costs for Touré	150,000 CFA	-----	----
	708,000 CFA	795.980 CFA	\$1,531

APPENDIX C: TECHNICAL DOCUMENTATION

C.1 Calculation of Oven Incline Angle

The following data is taken from the website

<http://aa.usno.navy.mil/data/docs/AltAz.html>, using an average latitude of 14°N and average longitude of 14°W for Senegal, and GMT.

The altitude of the sun at 13:00:

15-Jan	15-Feb	21-Mar	15-Apr	15-May	21-Jun
54.8°	63.1°	76.5°	85.9°	84.7°	80.5°
15-Jul	15-Aug	21-Sep	15-Oct	15-Nov	21-Dec
82.6°	89.8°	76.2°	66.8°	57.0°	52.5°

The complements of the above altitudes were averaged with the months of March to August weighted more heavily, since these are the months the oven will be used the most, yielding an oven incline angle of 13°.

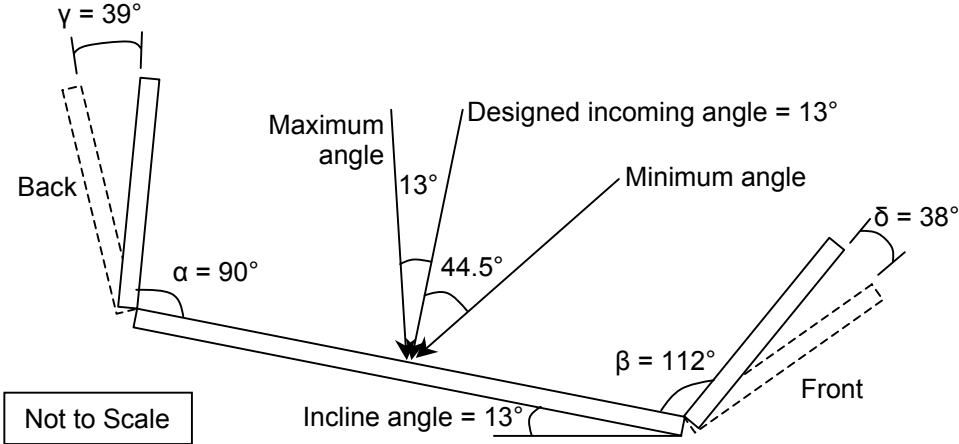
This value was then subtracted from the complement angle of the sun altitude for all months, from 10:00 to 15:00, the time when the oven would be most useful. This data is in the following table:

	15-Jan	21-Mar	15-May	21-Jun	15-Aug	21-Sep	15-Nov	21-Dec
10:00	44.5°	34.2°	28.5°	30.0°	33.7°	30.9°	38.3°	43.7°
11:00	33.7°	20.3°	14.3°	16.4°	16.2°	17.1°	28.0°	33.7°
12:00	25.6°	7.6°	0.5°	3.6°	1.6°	5.2°	21.1°	26.7°
13:00	22.2°	0.5°	-7.7°	-3.5°	-12.8°	0.8°	20.0°	24.5°
14:00	24.6°	6.5°	4.0°	4.5°	1.5°	9.2°	25.0°	27.7°
15:00	32.0°	18.9°	18.0°	17.3°	16.0°	22.2°	34.4°	35.4°

From the above data, the maximum altitude of the sun is approximately 13° less than the designed incoming angle of 13°, when the sun is directly overhead. This is taken to be the maximum sun altitude. The minimum altitude is 44.5° greater than the designed angle, during the early morning in January. The extreme values were used to determine the angles the reflectors should be set at.

The front reflector is important in directing the sun's rays with incoming altitudes between the maximum angle and the designed angle. The value of the maximum altitude is used along with some trigonometry to determine the reflector angle, so that all the incoming light between these two angles will be reflected into the solar oven box. Similar analysis was done for the back reflector, with the incoming solar rays with incoming angles between the

minimum altitude and the designed angle. The resulting values were to open the front reflector at 112° from the plane of the windows, angle β in the following drawing, and for the back reflector at 90° , angle α . Similar calculations were performed to determine the range of motion the reflectors should have. For the back reflector, the minimum incoming angle was used to determine the necessary angle γ , 39° , and for the front reflector, the maximum income angle was used to determine angle δ , 38° .

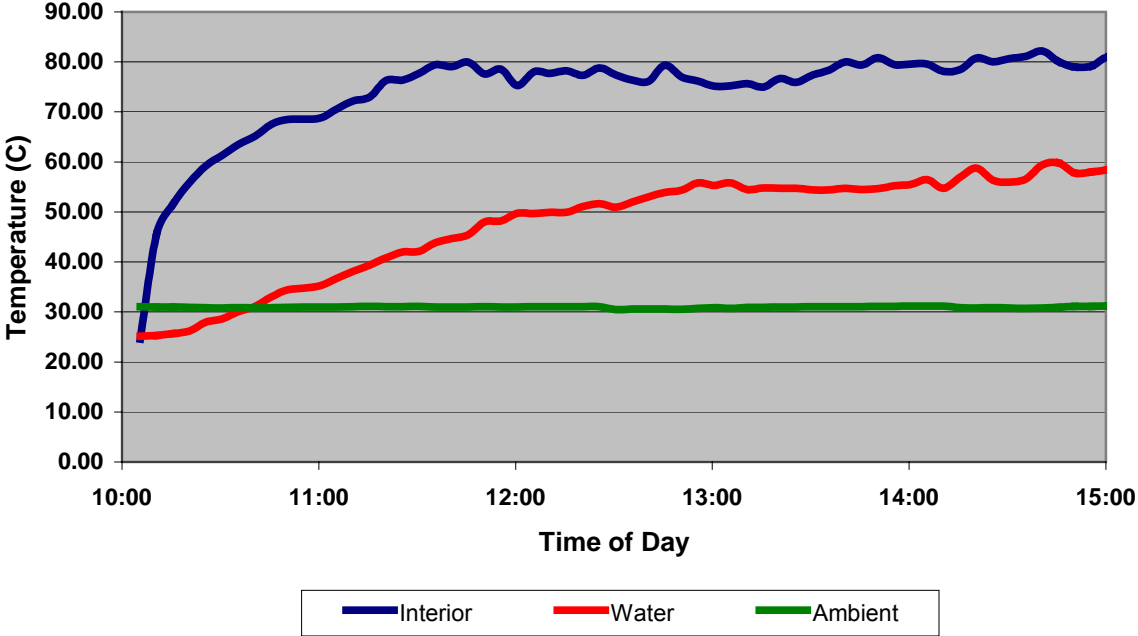


C.2 Power Calculation and Temperature Tests

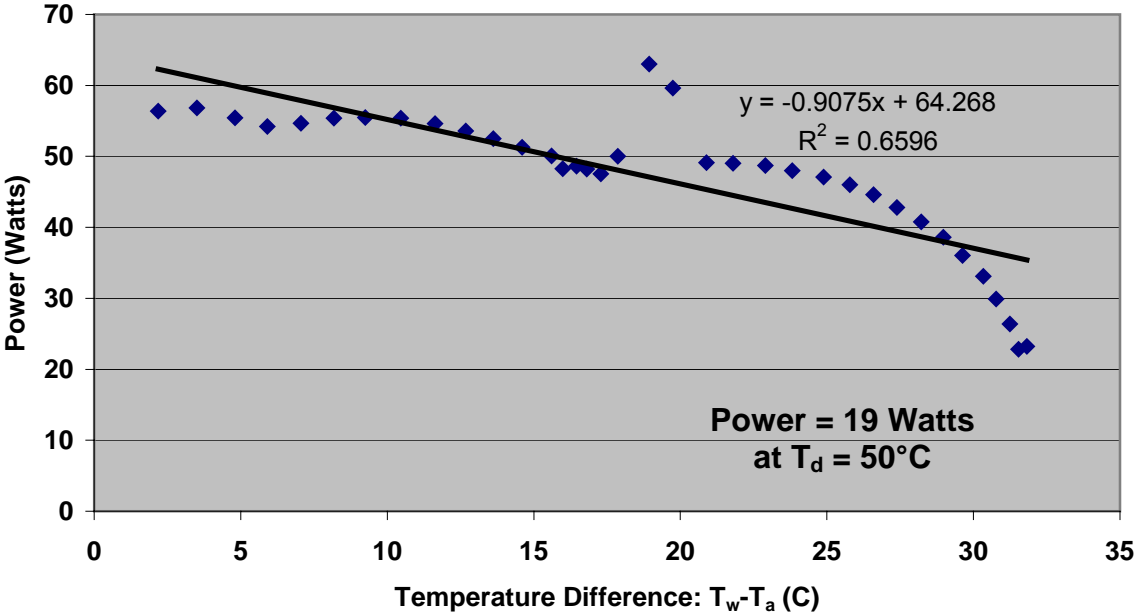
The following table shows a comparison of the maximum temperature reached during testing for various locations of the old and new ovens. Location descriptions are given in Figure 16. Further testing is necessary for the new oven to compare the remaining locations. Preliminary results show the new oven has higher maximum temperatures.

	Old oven (°C)	New oven (°C)
Inside back left, behind pot	95.76	113.41
Inside front left	76.55	
In between glass	66.82	
Middle of interior right	105.47	104.94
Inside bottom right	103.28	114.20
Inside pot, water temperature	67.07	73.55
Outside front left	60.57	46.32
Bottom of wood frame, seal	50.11	
Top of pot lid (outside)	99.04	105.07
Left reflector	30.30	
Ambient temperature	31.90	30.23

The following graph is a typical temperature profile for the temperature testing. The green line is the ambient temperature, the blue line is the temperature in the interior of the oven, and the red line is the temperature of the water.



Following the ASAE X580 Standard as given in Appendix C.5 and using the ambient temperature and water temperature data, the standard power of the oven can be calculated. The standard power is calculated and plotted as a function of temperature difference, the difference between the water temperature and the ambient temperature. A linear trendline is fitted to the data. The power of the oven is calculated using the trendline equation with a temperature difference of 50°C. The graph below uses data taken on two separate days. There were a few problems with the data collection due to the error of the thermocouple measurement, which was ±1°C. As a result, the measured water temperature fluctuated, with negative differences in temperature from one reading to the other. This should not occur, since the water temperature should be constantly rising once the oven is exposed to the sun. To account for this error, a curve was fit to the data and values calculated using this formula were used for the water temperature. The linear regression trendline has an R² value less than 0.75, as specified by the standard, but the standard power is presented since it is calculated using the best data available. A similar calculation was performed for the data from the new oven, yielding a power of 28 Watts for a temperature difference of 50°C with an R² of 0.36.



C.3 Material Characterization Tests

The following graph, from the testing of rice hulls, is a typical temperature profile from the conductivity tests. The ambient temperature, T_a , stays approximately constant, while the temperature in the box drops. The voltage controls how fast the temperature in the box, T_b , drops. The experiment is stopped when the difference between T_a and T_b is less than 1°C , T_b stays constant, and the difference between the top and bottom plates, T_c and T_f respectively, is constant. Each test takes 4-6 hours to run. The conductivity is then calculated using the following formula:

$$\lambda = \frac{e}{S(T_c - T_f)} \left[\frac{V^2}{R} - C(T_b - T_a) \right]$$

where

λ is the conductivity $\left[\frac{\text{W}}{\text{m}^\circ\text{C}} \right]$

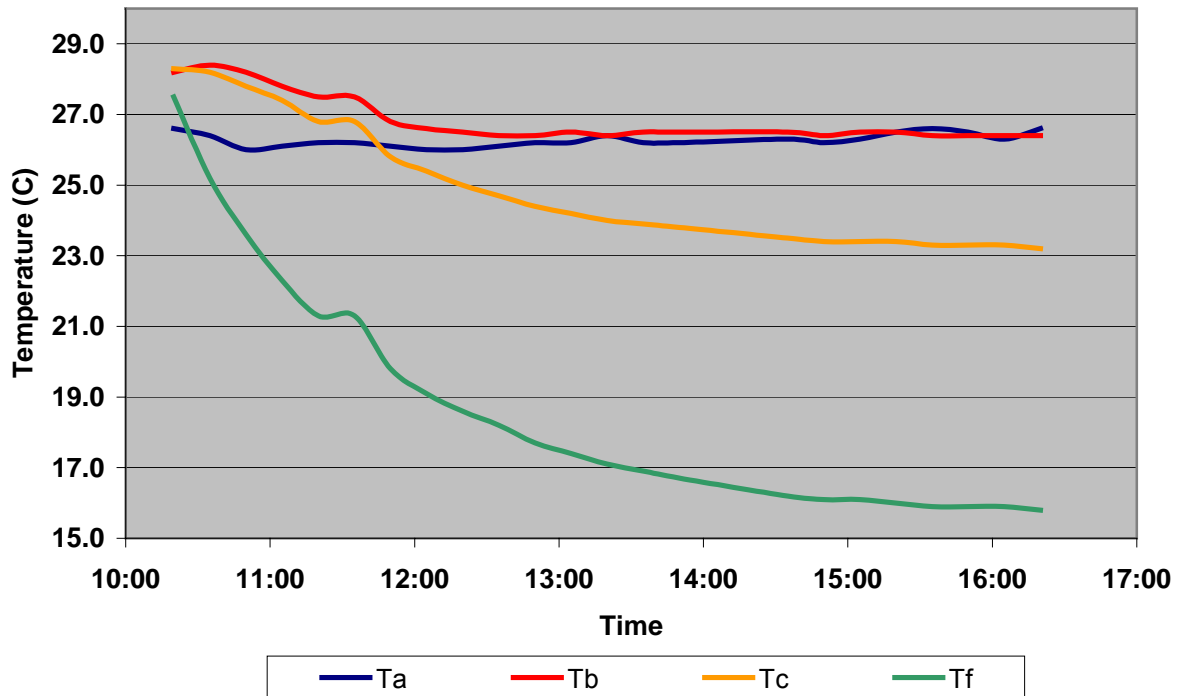
e is the sample thickness

S is the sample area

V is the voltage

R is the resistance of the experimental box, constant for each set-up

C is a constant for the experimental box.



The following graph, from a test of wood shavings, is a typical temperature profile graph for the diffusivity tests. The test is run until the temperature of the top plate starts to drop. The diffusivity is then calculated using the following formula:

$$a_1 = \frac{e^2}{t_{5/6}^2} (1.15t_{5/6} - 1.25t_{2/3})$$

$$a_2 = \frac{e^2}{t_{5/6}^2} (0.761t_{5/6} - 0.926t_{1/2})$$

$$a_3 = \frac{e^2}{t_{5/6}^2} (0.617t_{5/6} - 0.862t_{1/3})$$

where

e is the thickness of the sample

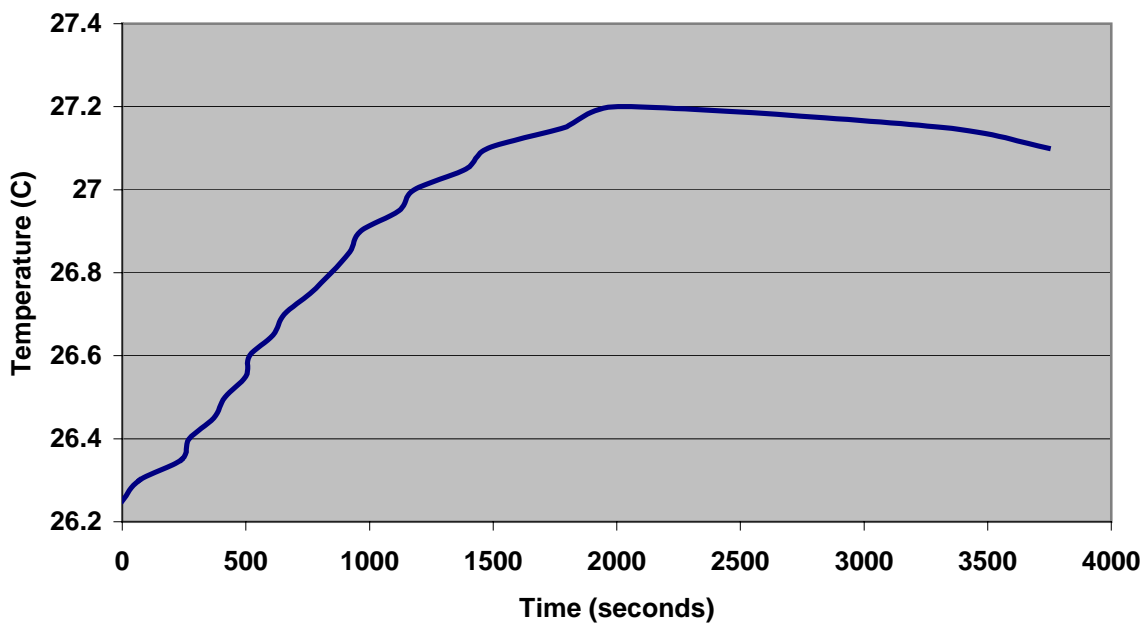
$t_{1/3}$ is the time it takes for the temperature to reach 1/3 of the maximum temperature

$t_{1/2}$ is the time it takes for the temperature to reach 1/2 of the maximum temperature

$t_{2/3}$ is the time it takes for the temperature to reach 2/3 of the maximum temperature

$t_{5/6}$ is the time it takes for the temperature to reach 5/6 of the maximum temperature.

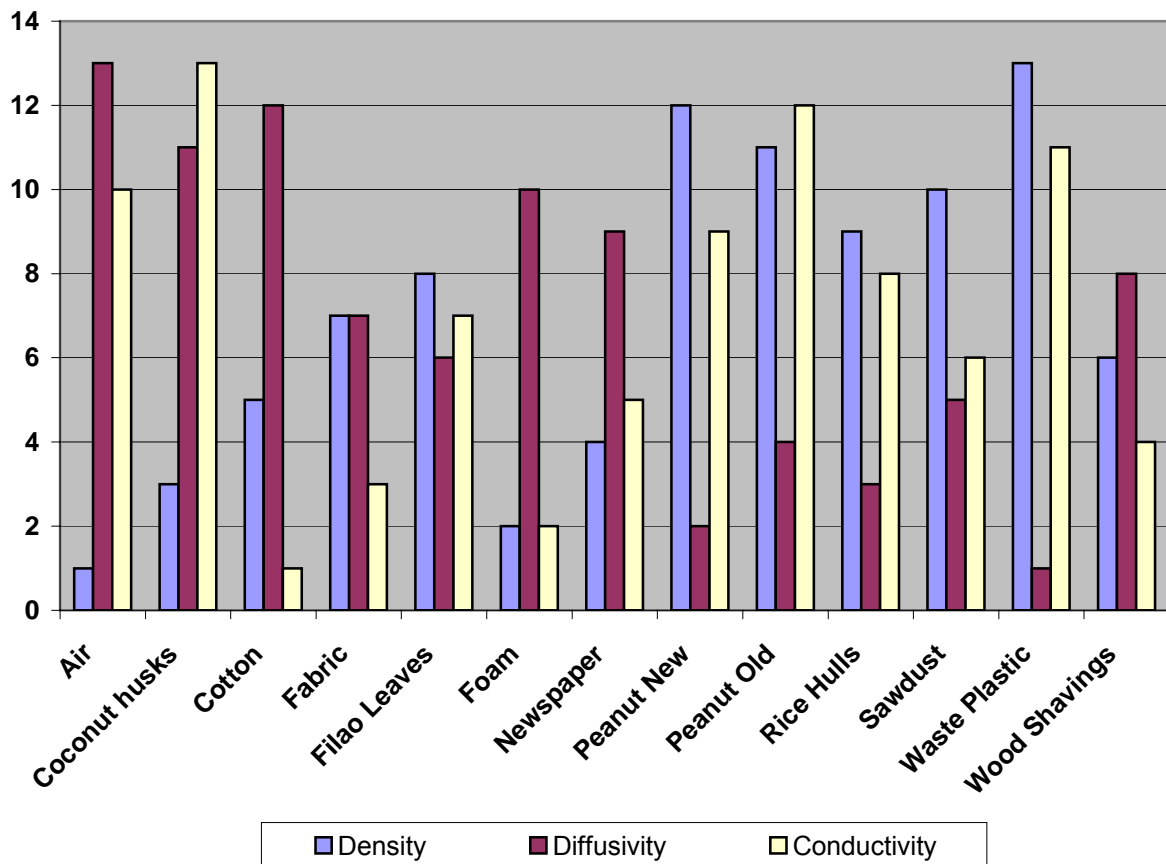
The diffusivity [m^2/s] is the average of a_1 , a_2 , and a_3 . To calculate $t_{1/3}$, $t_{1/2}$, $t_{2/3}$, and $t_{5/6}$, a polynomial trendline is fit to the data and the resulting formula is used to calculate the time.



The densities of the materials used, tested conductivities, and tested diffusivities are as follows:

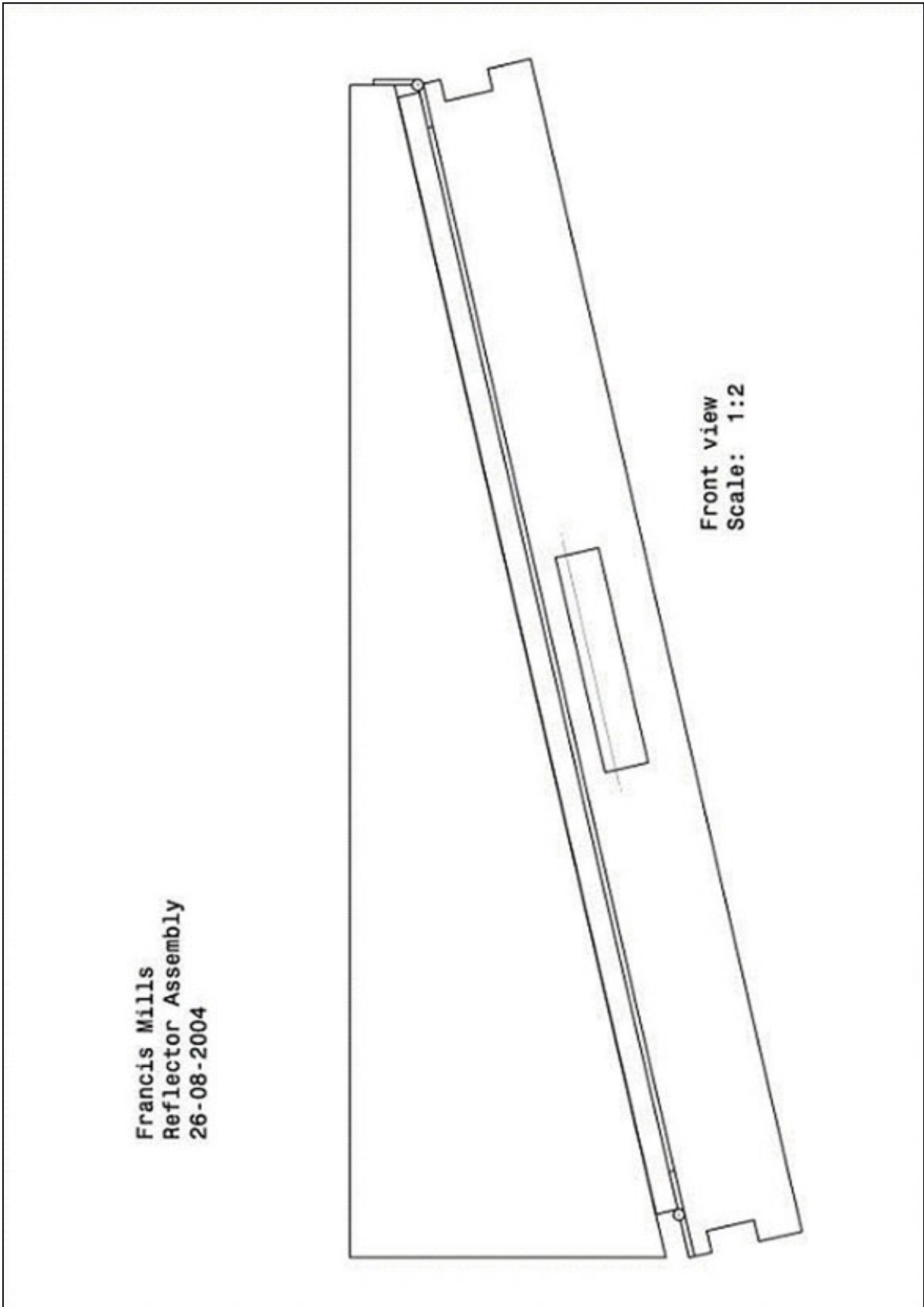
Material	Density (kg/m ³)	Conductivity (W/m°C)	Diffusivity (m ² /s)
Air	0.00	0.067	2.74E-06
Coconut husks	25.71	0.074	9.00E-07
Cotton	57.85	0.042	1.28E-06
Fabric	96.41	0.049	4.33E-07
Filao Leaves	133.37	0.062	3.47E-07
Foam	17.68	0.046	8.82E-07
Newspaper	28.92	0.059	7.28E-07
Peanut Shells (New)	186.39	0.066	2.06E-07
Peanut Shells (Decomposed)	162.29	0.073	2.55E-07
Rice Hulls	134.97	0.064	2.26E-07
Sawdust	155.86	0.061	2.70E-07
Waste Plastic	374.39	0.070	1.01E-07
Wood Shavings	91.59	0.056	4.88E-07

The density, diffusivity, and conductivity of each material are ranked in the graph below. The lower the rank, the lower the value. For example, cotton has a conductivity rank of 1, so it has the lowest conductivity.



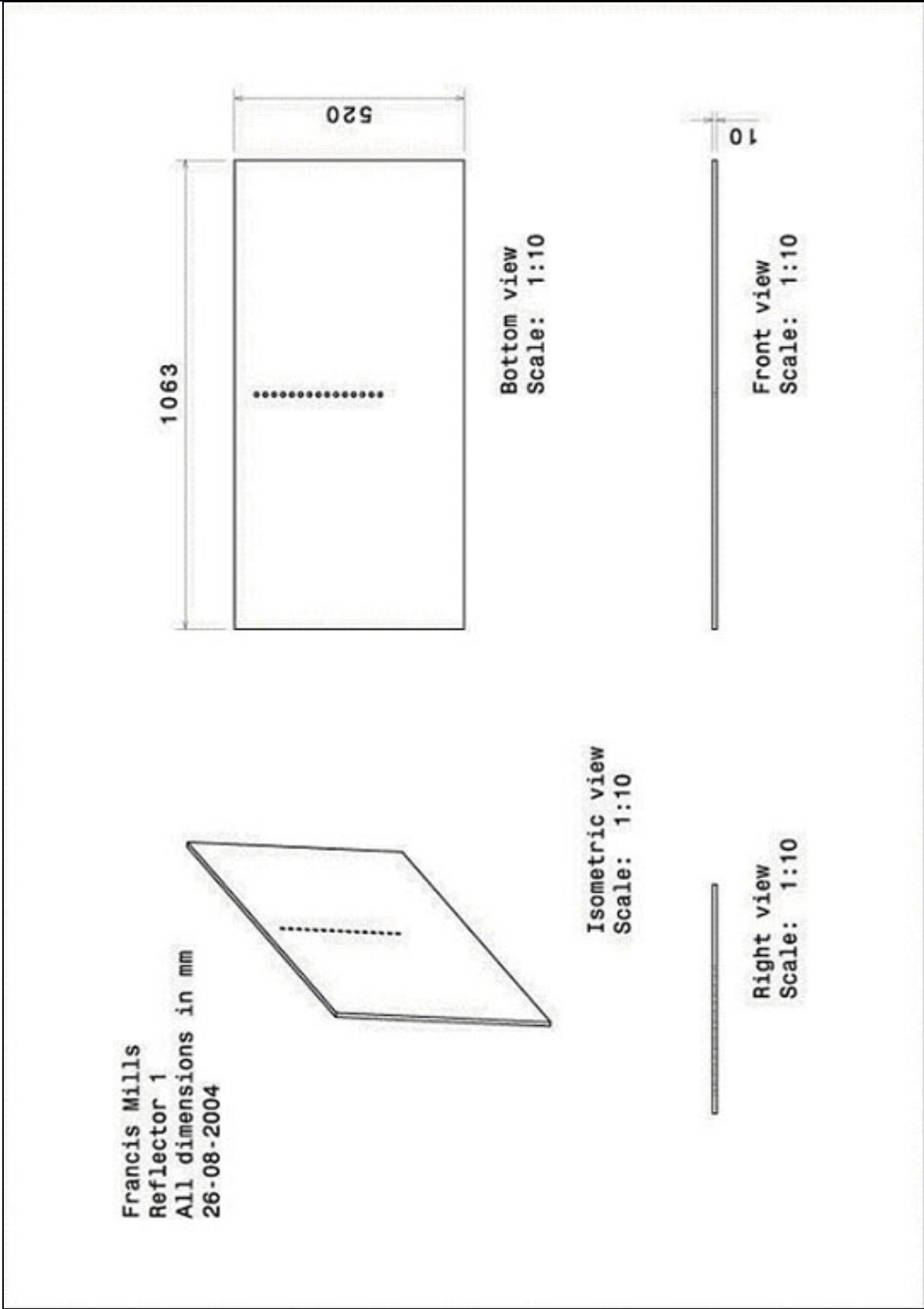
C.4 Detailed Design Drawings

Not to scale, original size: A4



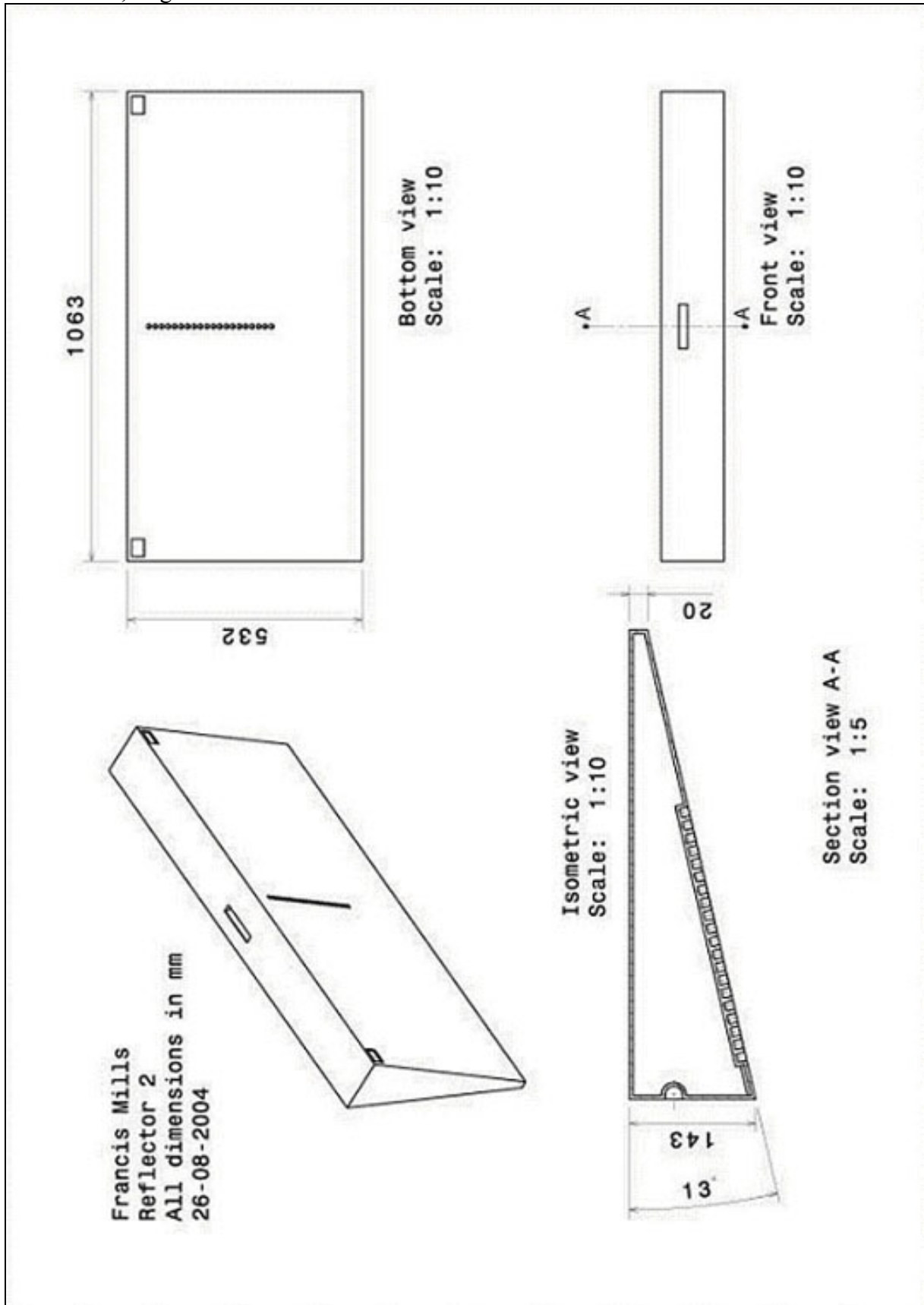
C.4 Detailed Design Drawings (cont.)

Not to scale, original size: A4



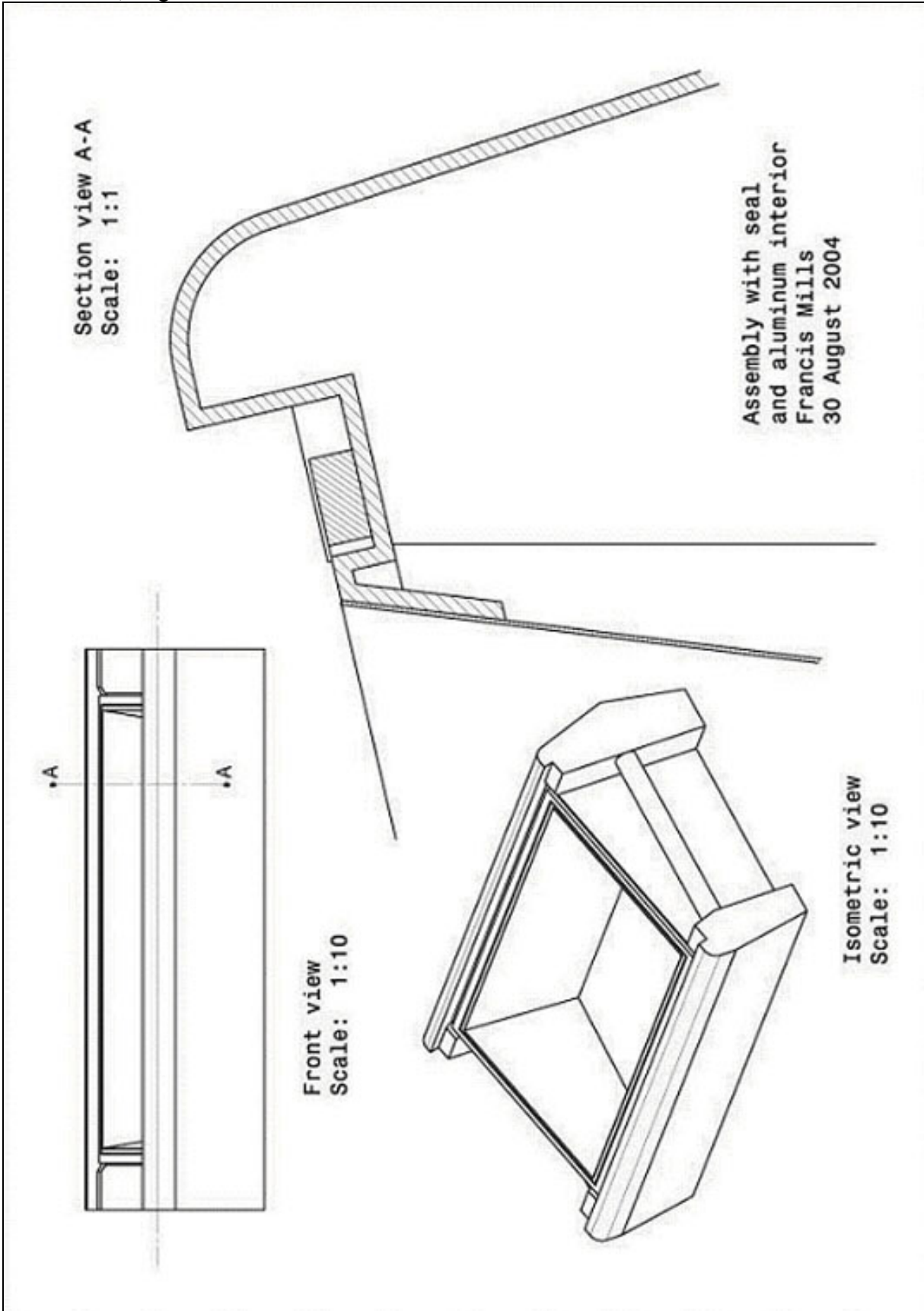
C.4 Detailed Design Drawings (cont.)

Not to scale, original size: A4



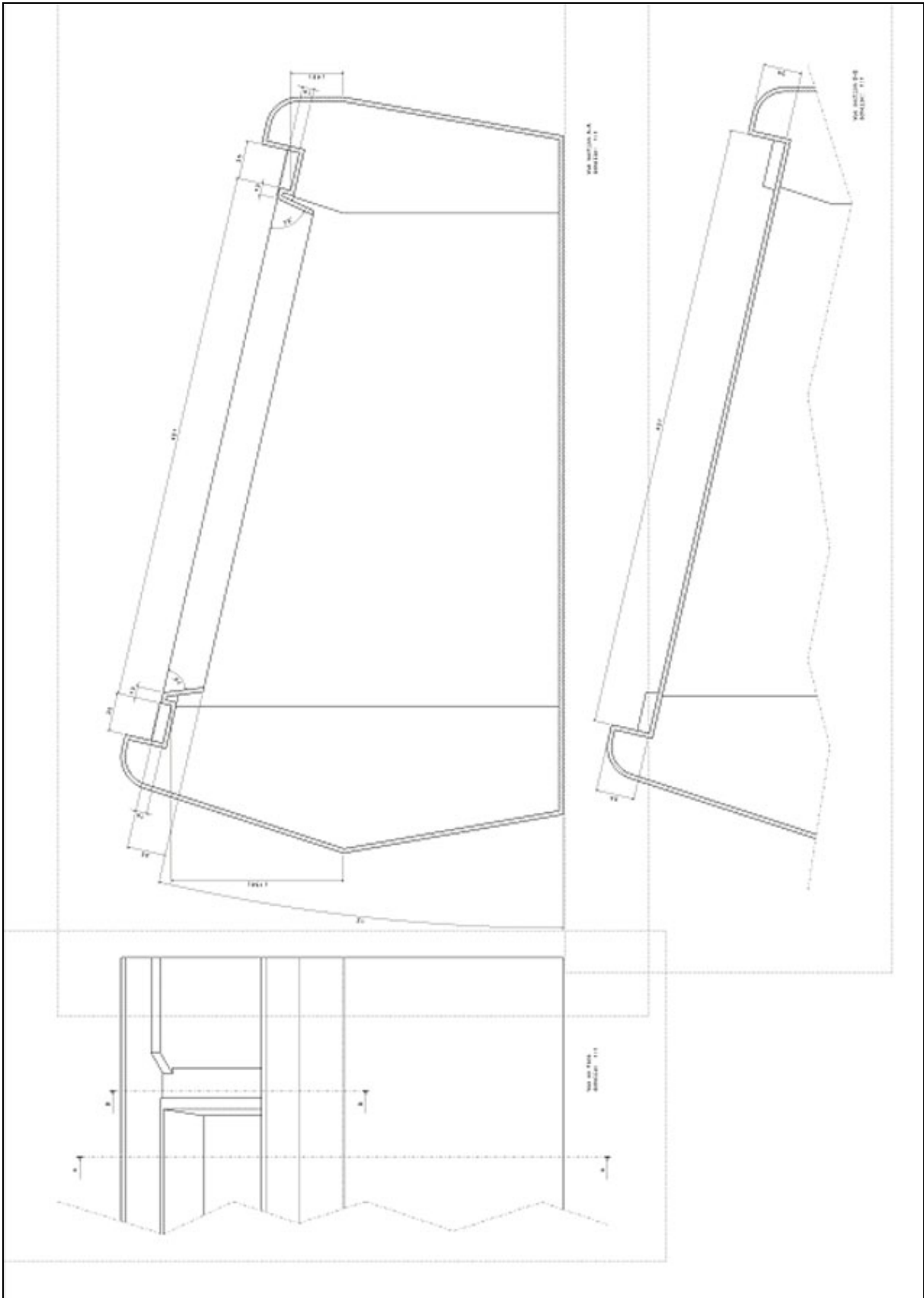
C.4 Detailed Design Drawings (cont.)

Not to scale, original size: A4



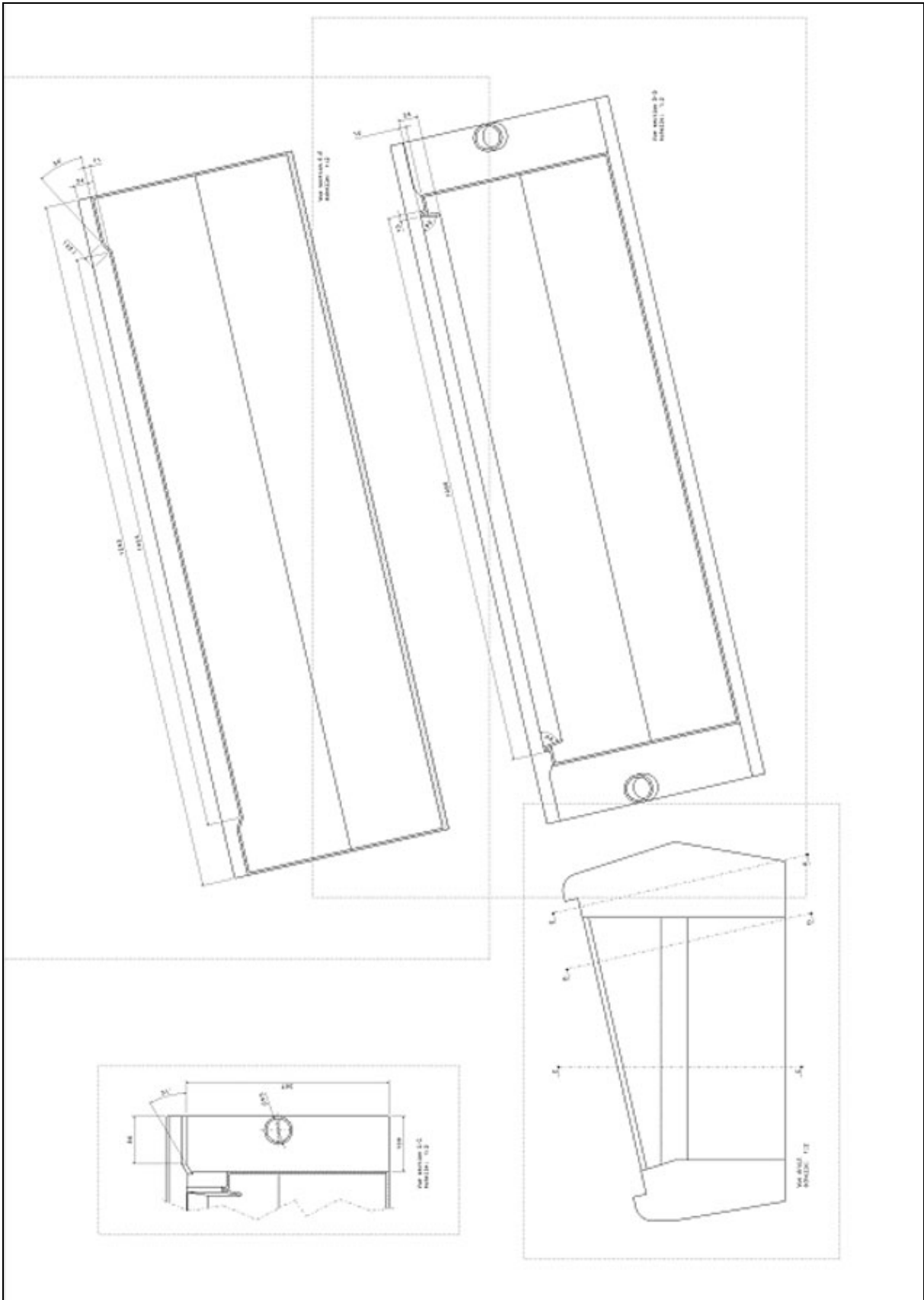
C.4 Detailed Design Drawings (cont.)

Not to scale, original size: A0, Page 2 of 3



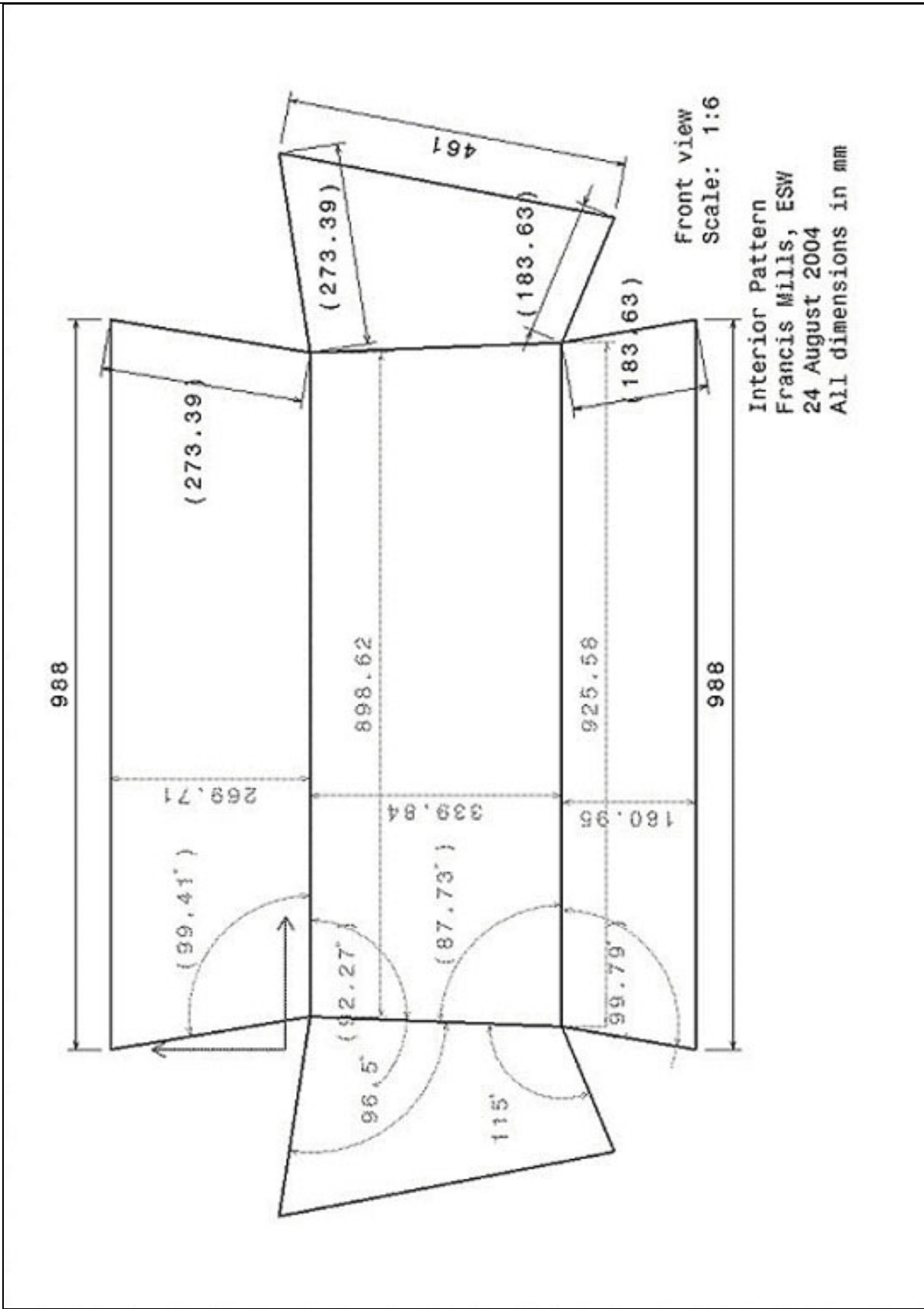
C.4 Detailed Design Drawings (cont.)

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C.4 Detailed Design Drawings (cont.)

Not to scale, original size: A4



C.5 List of Materials

Model Structure	Qty.	Source/Materials/Process	Model Filename Drawing <i>Filename</i>
Assembled Solar Oven			OVEN.CATProduct
Cooking Box Assembly			BOTTOM.CATProduct <i>BOTTOM_ASSY_A4.CATDrawing</i>
Case, Exterior	1	Roto-Molded at TransTech	BOX2.CATPart <i>BOX2A0.CATDrawing</i>
Aluminum Liner	1	SAII	ALUMINUM.CATPart <i>ALUMINUM.CATDrawing</i>
Paint		Locally purchased	
Insulation	1	Locally fabricated	
Seal	1	Locally fabricated	SEAL.CATPart
Screws	~22	Locally purchased	
Sliding Assembly			TOP.CATProduct <i>TOP.CATDrawing</i>
Window Frame assembly			FRAME.CATPart
<i>Rails, Side</i>	2	<i>TransTech Plastic Wood</i>	
<i>Rails, End</i>	2	<i>TransTech Plastic Wood</i>	
<i>Rail, Middle</i>	1	<i>TransTech Plastic Wood</i>	
<i>Glass Panes</i>	4	<i>Glass wholesalers in Dakar</i>	
Reflector, Front	1	Roto-Molded at TransTech	REFLECTOR1.CATPart <i>REFLECTOR1_A4.CATDrawing</i>
Reflector, Rear	1	Press-Molded at TransTech	REFLECTOR2.CATPart <i>REFLECTOR2_A4.CATDrawing</i>
Struts	2	Locally fabricated	
Tensioning assembly	1	Locally fabricated	
Aiming Mirrors	2	Salvaged scraps	
Aluminum Foil	~1 m ²	Locally purchased	
Glue		Locally purchased	
Screws	~36	Locally purchased	
Hinges	6	Locally purchased	HINGE_1.CATProduct, HINGE_2.CATProduct, HINGE_HALF.CATPart

C.6 ASAE Test Standard X580

ASAE Standard: ASAE X580 (SE-414 Voting Draft revised by P. Funk on 04/03/2002)

Testing and Reporting Solar Cooker Performance

Developed by the Test Standards Committee at the Third World Conference on Solar Cooking (Coimbatore, Tamil Nadu, India, 9 January 1997); editorial revisions November 1998 and July 1999; revised March 2001 (Third Latin American Congress on Solar Cookers, La Ceiba, Atlintico, Honduras); edited and submitted for approval to ASAE Solar Energy Committee SE-414 (94th Annual International Meeting, Sacramento, California, USA) 31 July 2001; revised and resubmitted 15 March 2002.

SECTION 1 — PURPOSE AND SCOPE

- 1.1 This Standard is intended to
 - 1.1.1 Promote uniformity and consistency in the terms and units used to describe, test, rate and evaluate solar cookers, solar cooker components, and solar cooker operation.
 - 1.1.2 Provide a common format for presentation and interpretation of test results to facilitate communication.
 - 1.1.3 Provide a single measure of performance so consumers may compare different designs when selecting a solar cooker.
- 1.2 The scope of this Standard includes
 - 1.2.1 All solar powered batch-process food and water heating devices (solar cookers). Devices designed to desiccate (dryers) are not covered.
 - 1.2.2 Within the scope of this Standard a solar cooker shall be understood to include the cooking vessel(s) together with associated supporting, heat transfer and heat retention surfaces, heat storage and transfer media and associated pumps and controls, light transmitting and reflecting surfaces, and all associated adjustments, supports, and solar locating and tracking mechanisms as may be integral parts of a particular solar cooker.

SECTION 2 — NORMATIVE REFERENCES

IS 13429. 1992. Indian Standard- Solar Cooker- (3 Parts). Bureau of Indian Standards, New Delhi.

SECTION 3 — TERMINOLOGY

- 3.1 **Absorber plate:** Darkened surface converting light energy into thermal energy.
- 3.2 **Angle, Azimuth:** The angular displacement from south of the projection of beam radiation on the horizontal plane.
- 3.3 **Angle, Zenith:** The angle subtended by a vertical line to the zenith (point directly overhead) and a line directly to the sun.
- 3.4 **Beam Radiation:** Solar radiation received directly from the sun without atmospheric scattering.
- 3.5 **Box-type cooker:** A solar cooker with a well-insulated volume for the cooking vessel(s), typical designs having from zero to four plane mirrors.
- 3.6 **Concentrating-type cooker:** Any of various designs characterized by multiple plane or curved reflective surfaces. Many designs lack insulated walls but have large intercept areas to compensate for their comparatively greater heat loss.
- 3.7 **Intercept area:** The sum of the reflector and aperture areas projected onto the plane perpendicular to direct beam radiation. For convenience, use the average beam radiation zenith angle as calculated for the entire test period.
- 3.8 **Load:** The mass of water being heated by the solar cooker.
- 3.9 **Test:** All events and data comprising the measured solar heating of water in a device intended to cook food.

3.10 Tracking: Rotating the cooker in the horizontal plane to compensate for azimuth angle changes (box-type) or following the sun in two dimensions (concentrating-type).

SECTION 4 — GENERAL

4.1 This Standard specifies that test results be presented as cooking power, in Watts, normalized for ambient conditions, relative to the temperature difference between cooker contents and ambient air, both as a plot and as a regression equation for no less than 30 total observations over three different days.

4.2 This Standard specifies that cooking power be presented as a single number found from the above equation for a temperature difference of 50 C.

SECTION 5 — UNCONTROLLED (WEATHER) VARIABLES

5.1 Wind. Tests shall be conducted when wind is less than 1.0 ms^{-1} , measured at the elevation of the cooker being tested and within ten meters of it. Should wind exceed 2.5 ms^{-1} for more than ten minutes, discard that test data. If a wind shelter is required, 1) it shall be designed so as to not interfere with incoming total radiation and 2) The wind instrumentation shall be co-located with the cooker in the same wind shadow.

5.2 Ambient temperature. Tests should be conducted when ambient temperatures are between 20 and 35 C.

5.3 Water temperature. Test data shall be recorded while cooking vessel contents (water) is at temperatures between 5 C above ambient and 5 C below local boiling temperature.

5.4 Insolation. Available solar energy shall be measured in the plane perpendicular to direct beam radiation (the maximum reading) using a radiation pyranometer. Variation in measured insolation greater than 100 Wm^{-2} during a ten-minute interval, or readings below 450 Wm^{-2} or above 1100 Wm^{-2} during the test shall render the test invalid. For convenience, the pyranometer may be fixed on the cooker at the average beam radiation zenith angle as calculated for the entire test period.

5.5 Solar zenith and azimuth angle. Tests should be conducted between 10:00 and 14:00 solar time. Exceptions necessitated by solar variability or ambient temperature shall be specially noted.

SECTION 6 — CONTROLLED (COOKER) VARIABLES

6.1 Loading. Cookers shall have 7.0 kg potable water per square meter intercept area distributed evenly between the cooking vessels supplied with the cooker. If no cooking vessels are provided, inexpensive aluminum cooking vessels painted black shall be used.

6.2 Tracking. Azimuth angle tracking frequency should be appropriate to the cooker's acceptance angle. Box-type cookers typically require adjustment every 15 to 30 minutes or when shadows appear on the absorber plate. Concentrating-type units may require more frequent adjustment to keep the solar image focused on the cooking vessel or absorber. With box-type cookers, zenith angle tracking may be unnecessary during a two hour test conducted at mid-day. Testing should be representative of local conditions, *ie*; how the typical consumer is expected to use the cooker.

6.3 Temperature sensing. Water and air temperature should be sensed with thermocouples. Each thermocouple junction shall be immersed in the water in the cooking vessel(s) and secured 10 mm above the bottom, at center. Thermocouple leads should pass through the cooking vessel lid inside a thermally nonconductive sleeve to protect the thermocouple wire from bending and temperature extremes. The sleeve should be secured with 100% silicone caulk to reduce water vapor loss.

6.4 Water mass. The mass of water should be determined with an electronic balance to the nearest gram using a pre-wetted container.

SECTION 7 — TEST PROTOCOL

7.1 Recording. The average water temperature (C) of all cooking vessels in one cooker shall be recorded at intervals not to exceed ten minutes, and should be in units of Celsius to the nearest one tenth of a degree. Solar insolation (Wm^{-2}) and ambient temperature (C) shall be recorded at least as frequently. Record and report the frequency of attended (manual) tracking, if any. Report azimuth angle(s) during the test. Report the test site latitude and the date(s) of testing.

7.2 Calculating cooking power. The change in water temperature for each ten-minute interval shall be multiplied by the mass and specific heat capacity of the water contained in the cooking vessel(s). This product shall be divided by the 600 seconds contained in a ten-minute interval, as:

$$P = (T_f - T_i)MC_v/600 \quad [1]$$

where:

- P = cooking power (W)
- T_f = final water temperature
- T_i = initial water temperature
- M = water mass (kg)
- C_v = heat capacity ($4186 \text{ Jkg}^{-1}\text{K}^{-1}$)

7.3 Calculating interval averages. The average insolation, average ambient temperature, and average cooking vessel contents temperature shall be found for each interval.

7.4 Standardizing cooking power. Cooking power for each interval shall be corrected to a standard insolation of 700 Wm^{-2} by multiplying the interval observed cooking power by 700 Wm^{-2} and dividing by the interval average insolation recorded during the corresponding interval.

$$P_s = P_i(700/I_i) \quad [2]$$

where:

- P_s = standardized cooking power (W)
- P_i = interval cooking power (W)
- I_i = interval solar insolation (Wm^{-2})

7.5 Temperature difference. Ambient temperature for each interval is to be subtracted from the average cooking vessel contents temperature for each corresponding interval.

$$T_d = T_w - T_a \quad [3]$$

where:

- T_d = temperature difference (C)
- T_w = water temperature (C)
- T_a = ambient air temperature (C)

7.6 Plotting. The standardized cooking power, P_s , (W) is to be plotted against the temperature difference, T_d , (C) for each time interval.

7.7 Regression. A linear regression of the plotted points shall be used to find the relationship between cooking power and temperature difference in terms of intercept (W) and slope (WC^{-1}). No fewer than 30 total observations from three different days shall be employed. The coefficient of determination (r^2) or proportion of variation in cooking power that can be attributed to the relationship found by regression should be better than 0.75 or specially noted.

7.8 Single measure of performance. The value for standardized cooking power, P_s , (W) shall be computed for a temperature difference, T_d , of 50 C using the above determined relationship.

NOTE: for product labeling and sales literature an independent laboratory using a statistically adequate number of trials shall determine this number. While this value, like the fuel economy rating of an automobile, is not a guarantee of performance, it provides consumers with a useful tool for comparison and product selection.

7.9 Reporting. A plot of the relationship between standardized cooking power and temperature difference shall be presented with the equation. The report shall also state the standardized cooking power at a temperature difference of 50 C.

SECTION 8 — REFERENCES

Funk, P.A. 2000. Evaluating the international standard procedure for testing solar cookers and reporting performance. *Solar Energy* **68**(1):1-7.

Mullick S.C., Kandpal T.C. and Saxena A.K. 1987. Thermal test procedure for box-type solar cookers. *Solar Energy* **39**(4), 353-360.

APPENDIX D: RAINWATER COLLECTION SYSTEM

We began this sub project by evaluating the building and available components. Second, we designed a system that allows for future capacity increases, and third, installed the system.

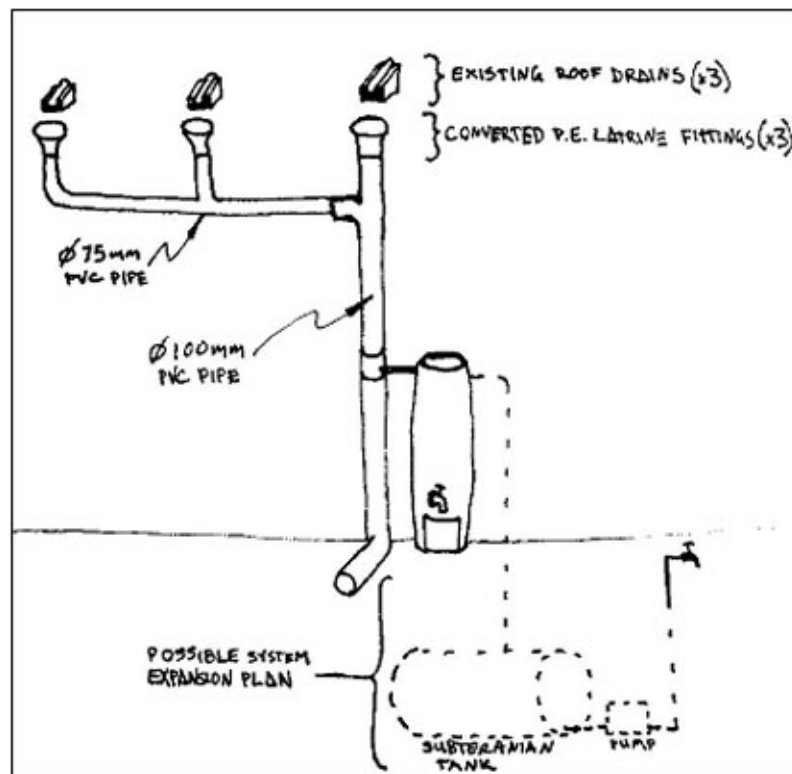
The roof of CRESP's office had three existing, cast concrete downspouts along its eastern edge. By letting a garden hose run on the roof, we verified that the roof would empty water through all three downspouts. We also confirmed that standing water does not overflow into the doorway of the interior stairwell. The collection of parts shipped with the tank (see below) included a diversion fitting supplied by Cloudburst. It was designed for 100 mm diameter pipe and is intended for placement in series with the primary downspout. It intercepts much of the water that flows along the interior surfaces of the downspout and directs it through a flexible hose that empties into the top of the tank. Water is dispensed through a side-mounted faucet near its bottom. When the tank is full, the diverter allows the surplus water to continue to the downspout's conventional exit.



We designed within these constraints. We chose PVC pipe due to its wide availability as a staple of Senegal's booming residential construction sector. Although we were unable to readily locate certain, specific fittings for joining these pipes, we were able to make substitutions. We created a branch system that connected all three drains to one common downspout. Pieces normally used for toilet drains served as non-destructive collectors for the three roof spouts. For the horizontal branch, we specified at least 2 cm of drop per one meter of run and insured that the system would not cover any of the building's window openings.

CRESP's staff, especially Boubacar and Ronald, was essential in purchasing supplies from local suppliers. The plumber hired by CRESP was much less helpful. After half a day's worth of his time, we completed the rest of the installation on our own. A tool of particular importance during installation was CRESP's electric hammer drill with masonry bits. We used the drill to bore the holes by which we fastened the tank and pipe clamps to the building.

Alone, the 250L tank could never provide enough water for the garden considering that roughly 750L of water are used per day during the dry season, based on our observations of CRESP's gardener. Our design was intended to allow system expansion (see below) and at the time of our departure, Ismael Diallo had already expressed interest in upgrading the system. Although our other projects prohibited us from spending significant time researching this field, countless design guides, reference lists, sample calculations, and decision trees exist for this technology. In the case of system expansion, those involved should consider reviewing the vast amount of rainwater collection literature available on the internet.



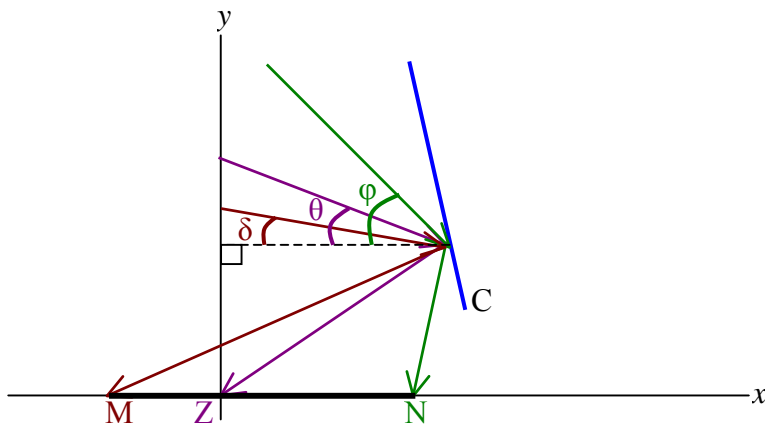
APPENDIX E: TRANSTECH REFLECTOR MODEL

The following is document given to TransTech Industries describing the work done on their water heater reflector model.

E.1 Steps for Determining the Ideal Solar Water Heater Reflector Shape

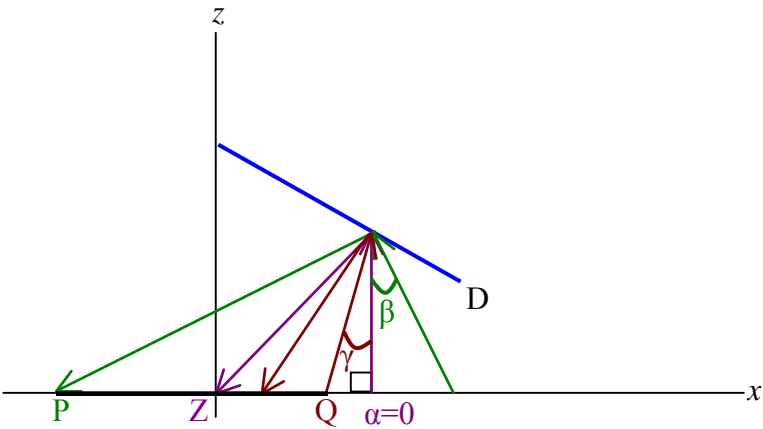
For the vertical (y-axis) direction in the x-y plane, assuming the sunlight is striking the reflector at a constant azimuth, parallel to the z-axis.

1. Find the average sunlight altitude (θ) for the intended period of operation.
2. Find the extreme maximum and minimum sunlight altitudes (ϕ and δ) for the intended period of operation.
3. Assume the light is to be collected at a Point 'Z'.
4. Assume that the reflector's surface begins at some Position 'C' above and to the side of Point 'Z'.
5. Calculate a function that includes Position 'C' and focuses the light at Point 'Z'.
6. For the same function, determine the focal points 'M' and 'N' for the extreme sunlight altitudes.
7. Prescribe a tank window or black surface pane that includes Points 'Z', 'M', and 'N'.



For the sunlight (z-axis) direction in the z-x plane, assuming the sunlight is striking the reflector at a constant azimuth, parallel to the z-axis, perform a similar analysis

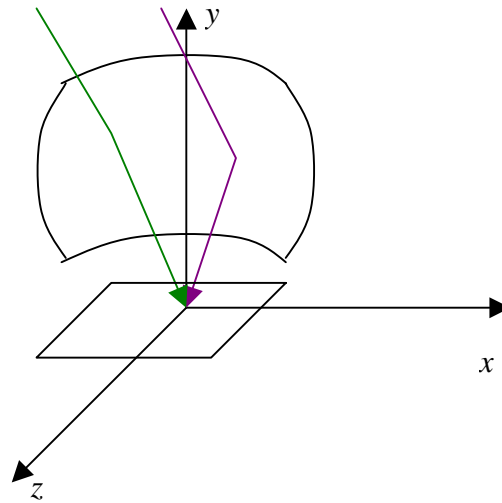
8. Find the average sunlight azimuth (α) for the intended period of operation and set that parallel to the z-axis.
9. Find the extreme maximum and minimum sunlight azimuths (β and γ) for the intended period of operation.
10. Assume the light is to be collected at a Point 'Z'.
11. Assume that the reflector's surface begins at some Position 'D' above and to the side the Point 'Z'.
12. Calculate a function that includes Position 'D' and focuses the light at Point 'Z'.
13. For the same function, determine the focal points 'P' and 'Q' for the extreme sunlight azimuths.
14. Prescribe a tank window or black surface pane that includes Points 'Z', 'P', and 'Q'.



E.2 Preliminary Work

Combining the 14 steps in Section 1, a rectangular surface can be found, containing Points M, N, P, and Q. This describes the ideal size of the tank opening. All the expected incoming light rays will be reflected into this opening, maximizing the heating of the water.

The angles of interest, θ , ϕ , δ , α , β , and γ are calculated using the altitude and position of the sun throughout the period of interest, the months of December to May, during the hours of 14:00 to 18:00. The calculations and description of the process are shown in Section 5.



A preliminary model and corresponding MatLab code has been written to begin this calculation. The code calculates the ideal shape in the x-y plane so that all the incoming light at angle θ will be reflected and concentrated at the origin. The program then checks to make sure the rays do end up at the origin, and calculates the furthest points where the extreme incoming light rays hit the horizontal (x-z) plane.

To approximate a three-dimensional model, the program then discretizes the y-axis and calculates a similar x-z curve at each y-point. Plotting these discrete lines yields a first order approximation to how the three-dimensional surface will look. The derivation of the equations that are used, along with the MatLab code are in Sections 3 and 4.

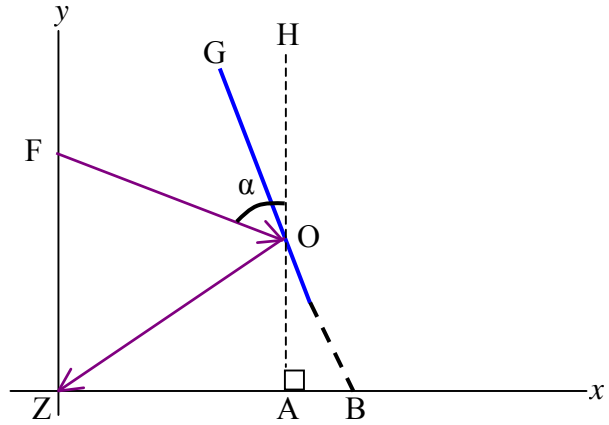
This is only a preliminary approximation and more work needs to be done to develop a more accurate three-dimensional model along with refining the equations to work with all incoming light conditions. Currently the model does not work for extreme angles, the light is directed behind the reflector, which is not possible. By varying the incoming angle θ , and correspondingly varying ϕ and δ , this problem can be mitigated. Further investigation needs to be done to optimize the angle θ that is used, perhaps choosing a value halfway in between ϕ and δ . This may create a shape that better captures the sunlight throughout the entire day. Additionally, negative values of x need to be accounted for in the x-z curve calculation. The program currently does not handle these values correctly. Also, a similar calculation needs to be added to determine the points where the light from the extreme azimuths hit the horizontal surface (Points P and Q), Steps 13 and 14 in Section 1.

E.3 Equation Derivation

Line \overline{GB} represents the slope of the reflector surface at Point O.

Line \overline{HA} represents a perpendicular line relative to the x-axis at Point O.

Line \overline{FO} represents an incoming light ray at angle α from perpendicular hitting Point O. Line \overline{OZ} represents the path of the reflected light ray from Point O.



Incoming light (at angle α from perpendicular) hits the reflector and reflects back at the same angle relative to the surface, so $\angle ZOB = \angle FOG$ (1)

Since they are opposite angles, $\angle GOH = \angle AOB$ (2)

From the definition of slope and trigonometry,

$$\tan \angle AOB = \frac{\Delta x}{-\Delta y} = -f'(y) \quad (3)$$

$$\angle AOB = \tan^{-1}(-f'(y))$$

From trigonometry,

$$\tan \angle ZOA = \frac{x}{y} = \frac{f(y)}{y} \quad (4)$$

$$\angle ZOA = \tan^{-1}\left(\frac{f(y)}{y}\right)$$

From trigonometry,

$$\begin{aligned} \angle ZOA &= \angle ZOB - \angle AOB \\ \angle ZOB &= \alpha - \angle GOH = \alpha - \angle AOB \quad (\text{from Eqn. 2}) \end{aligned}$$

Thus,

$$\angle ZOA = \alpha - 2\angle AOB \quad (5)$$

Combining Equations 3, 4, and 5:

$$\tan^{-1}\left(\frac{f(y)}{y}\right) = \alpha - 2 \tan^{-1}(-f'(y))$$

Simplifying:

$$f'(y) = -\tan\left[\frac{1}{2}\left(\alpha - \tan^{-1}\left(\frac{f(y)}{y}\right)\right)\right] \quad (6)$$

Incoming light altitude (θ) is relative to the horizon (x-axis), so

$$\alpha = \frac{\pi}{2} - \theta$$

and Equation 6 can be rewritten:

$$f'(y) = -\tan\left[\frac{1}{2}\left(\frac{\pi}{2} - \theta - \tan^{-1}\left(\frac{f(y)}{y}\right)\right)\right] \quad (7)$$

This equation can be solved in MatLab by discretizing the equation into:

$$\begin{aligned} x_i &= x_{i-1} + f'(y_{i-1})\Delta y \\ y_i &= y_{i-1} + \Delta y \end{aligned} \quad (8)$$

$$f'(y_i) = -\tan\left[\frac{1}{2}\left(\frac{\pi}{2} - \theta - \tan^{-1}\left(\frac{x_i}{y_i}\right)\right)\right]$$

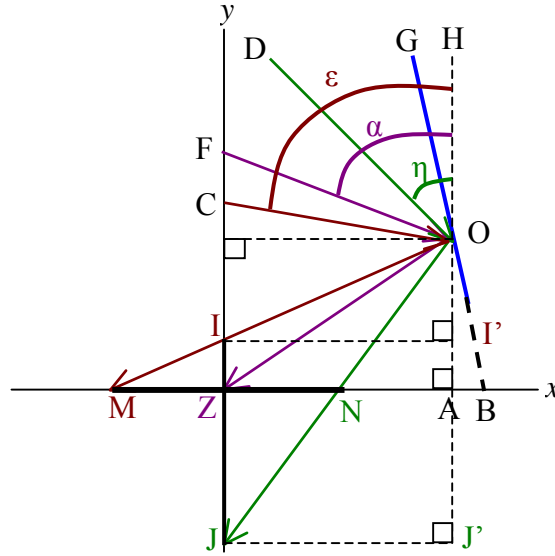
A similar derivation can be performed with a positive slope for the reflector and results in the same set of equations as Equation 8.

The following equations are used to determine Points M and N along the x-axis (assuming the tank surface is horizontal) and similar Points I and J along the y-axis (if a vertical tank surface is used).

Starting with the minimum altitude light ray, angle ε from vertical (the complement of δ).

Line segments are the same as descriptions given above.

Line \overline{CO} represents an incoming light ray at angle α from perpendicular hitting Point O. Line \overline{OM} represents the path of the reflected light ray from Point O.



Incoming light rays hit the reflector and reflect back at the same angle relative to the surface, so

$$\begin{aligned} \angle FOG &= \angle ZOB \\ \angle COG &= \angle MOB \end{aligned} \quad (1)$$

From trigonometry for the minimum x (Point M),

$$\angle MOZ = \angle FOC = \varepsilon - \alpha$$

$$\tan \angle ZOA = \frac{x}{y} = \frac{x}{f(x)}$$

$$\angle ZOA = \tan^{-1} \left(\frac{x}{f(x)} \right)$$

$$\angle MOA = \angle MOZ + \angle ZOA = \varepsilon - \alpha + \tan^{-1} \left(\frac{x}{f(x)} \right)$$

$$\tan \angle MOA = \frac{\overline{MA}}{f(x)}$$

$$\overline{MA} = f(x) \tan \angle MOA = f(x) \tan \left[\tan^{-1} \left(\frac{x}{f(x)} \right) + (\varepsilon - \alpha) \right]$$

$$M = x - \overline{MA} = x - f(x) \tan \left[\tan^{-1} \left(\frac{x}{f(x)} \right) + (\varepsilon - \alpha) \right]$$

From trigonometry for the maximum y (Point I),

$$I = f(x) - \overline{I'O}$$

$$\angle IOA = \angle MOA$$

$$\tan \angle IOA = \frac{x}{\overline{I'O}}$$

$$\overline{I'O} = \frac{x}{\tan \angle IOA}$$

$$I = f(x) - \frac{x}{\tan \left(\tan^{-1} \left(\frac{x}{f(x)} \right) + (\varepsilon - \alpha) \right)}$$

A similar derivation is done with the maximum altitude light ray, angle η from vertical (the complement of ϕ).

Line segments are the same as descriptions given above.

Line \overline{DO} represents an incoming light ray at angle α from perpendicular hitting Point O. Line \overline{OJ} represents the path of the reflected light ray from Point O.

Incoming light rays hit the reflector and reflects back at the same angle relative to the surface, so

$$\angle FOG = \angle ZOB \quad (1)$$

$$\angle DOG = \angle JOB$$

From trigonometry for the maximum x (Point N),

$$\angle FOD = \angle ZON = \alpha - \eta$$

$$\tan \angle ZOA = \frac{x}{y} = \frac{x}{f(x)}$$

$$\angle ZOA = \tan^{-1} \left(\frac{x}{f(x)} \right)$$

$$\angle NOA = \angle ZOA - \angle ZON = \tan^{-1} \left(\frac{x}{f(x)} \right) - (\alpha - \eta)$$

$$\tan \angle NOA = \frac{\overline{NA}}{f(x)}$$

$$\overline{NA} = f(x) \tan \angle NOA = f(x) \tan \left[\tan^{-1} \left(\frac{x}{f(x)} \right) - (\alpha - \eta) \right]$$

$$N = x - \overline{NA} = x - f(x) \tan \left[\tan^{-1} \left(\frac{x}{f(x)} \right) - (\alpha - \eta) \right]$$

From trigonometry for the minimum y (Point J),

$$J = f(x) + \overline{J'O}$$

$$\angle JOA = \angle NOA$$

$$\tan \angle JOA = \frac{x}{\overline{J'O}}$$

$$\overline{J'O} = \frac{x}{\tan \angle JOA}$$

$$J = f(x) - \frac{x}{\tan\left(\tan^{-1}\left(\frac{x}{f(x)}\right) - (\alpha - \eta)\right)}$$

This equation can be solved in MatLab by discretizing the equation into:

$$M_i = x_i - y_i \tan\left(\tan^{-1}\left(\frac{x_i}{y_i}\right) + (\varepsilon - \alpha)\right)$$

$$N_i = x_i - y_i \tan\left(\tan^{-1}\left(\frac{x_i}{y_i}\right) - (\alpha - \eta)\right)$$

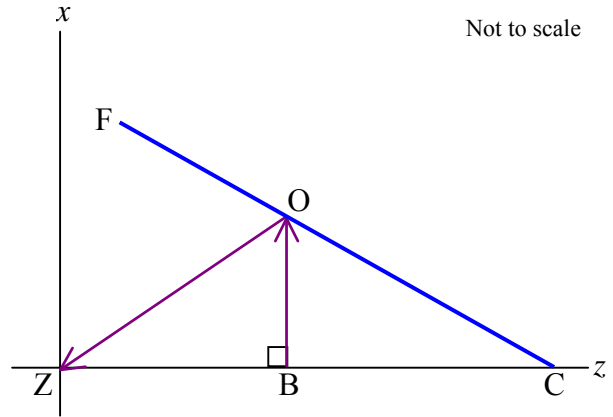
$$I_i = y_i - \frac{x_i}{\tan\left(\tan^{-1}\left(\frac{x_i}{y_i}\right) + (\varepsilon - \alpha)\right)}$$

$$J_i = y_i - \frac{x_i}{\tan\left(\tan^{-1}\left(\frac{x_i}{y_i}\right) - (\alpha - \eta)\right)}$$

A preliminary 3-dimensional model has been created in MatLab, using the assumption that the incoming solar azimuth is parallel to the z-axis.

Line \overline{FO} represents the slope of the reflector surface at Point O.

Line \overline{BO} represents an incoming light ray parallel to the z-axis hitting Point O. Line \overline{OZ} represents the path of the reflected light ray from Point O.



Incoming light hits the reflector and reflects back at the same angle relative to the surface, so $\angle BOC = \angle ZOF$ (9)

From the definition of slope and trigonometry,

$$\tan \angle BOC = \frac{\Delta x}{-\Delta z} = -g'(z) \quad (10)$$

$$\angle BOC = \tan^{-1}(-g'(z))$$

From trigonometry,

$$\tan \angle ZBO = \frac{z}{x} = \frac{z}{g(z)}$$

$$\angle ZBO = \tan^{-1}\left(\frac{z}{g(z)}\right) \quad (11)$$

$$\angle ZOB = \frac{\pi}{2} - \angle ZBO$$

$$\angle ZOB = \frac{\pi}{2} - \tan^{-1}\left(\frac{z}{g(z)}\right)$$

From trigonometry,

$$\angle ZOB = \pi - 2\angle BOC \quad (12)$$

Combining Equations 10, 11, and 12:

$$\frac{\pi}{2} - \tan^{-1}\left(\frac{z}{g(z)}\right) = \pi - 2 \tan^{-1}(-g'(z))$$

Simplifying:

$$g'(z) = -\tan\left[\frac{1}{2}\left(\frac{\pi}{2} + \tan^{-1}\left(\frac{z}{g(z)}\right)\right)\right] \quad (13)$$

This equation can be solved in MatLab by discretizing the equation into:

$$\begin{aligned}
x_i &= x_{i-1} + g'(z_{i-1})\Delta z \\
z_i &= z_{i-1} + \Delta z \\
g'(z_i) &= -\tan\left[\frac{1}{2}\left(\frac{\pi}{2} + \tan^{-1}\left(\frac{z_i}{x_i}\right)\right)\right]
\end{aligned}
\tag{14}$$

This can be combined with the 2-dimensional case above and at each discrete point y , an x - z curve can be calculated and plotted.

E.4 MatLab Code

```
% reflector3d.m
%
% This program is a first-order three dimensional approximation of the
% ideal shape of the solar water heater reflectors for TransTech Industries
% (Dakar, Senegal).
%
% Written by Robin Liu (robinliu@alumni.princeton.edu) and Francis Joseph
% Mills IV (f-mills@alumni.northwestern.edu); interns for Engineers for a
% Sustainable World and ONG CRESP- Senegal; 25 August 2004

% set parameters
k = 50;
m = 40;
deltay=0.01;
deltaz=0.5;

%set initial conditions
x0=25;
y0=50;
z0=0;

%average incoming angle
theta = 60*(pi/180);
% compliment of incoming angle
alpha = (pi/2) - theta;

%calculate initial values
x(1)=x0;
y(1)=y0;
z(1)=z0;
slopey(1)=-tan(0.5*((pi/2) - theta) - atan(x(1)/y(1)));
slopez(1)=-tan(0.5*((pi/2)+atan(z(1)/x(1))));
hold on
for i = 1:k
    % set index and increment y
    if (i==1)
        index=1;
    else
        index = (i-1) * (m+1) + 1;
        y(index) = y(index - 1) + deltay;
    end
    % calculate new value of x
    if (index==1)
        x(index) = x(1);
    else
        x(index) = x(index - (m+1)) + slopey(index-(m+1))*deltay;
    end
    % calculate slope dx/dy at current point
    slopey(index) = -tan(0.5*((pi/2) - theta - atan(x(index)/y(index))));
    % reset z
    z(index) = z(1);
    % calculate slope of z with respect to x dx/dz
    slopez(index) = -tan(0.5*((pi/2)+atan(z(index)/x(index))));
    % at a constant y value, calculate the x-z curve (parallel to the
    % ground)
    for j = 1:m
        % set index
        indexz = index + j;
```

```

% calculate new value of z and the corresponding x value and slope
z(indexz) = z(indexz - 1) + deltaz;
x(indexz) = x(indexz - 1) + slopez(indexz-1)*deltaz;
slopez(indexz) = -tan(0.5*((pi/2)+atan(z(indexz)/x(indexz))));
% keep y and slope dx/dy the same
y(indexz) = y(index);
slopey(indexz) = slopey(index);
% save values into separate arrays so they can be plotted
xz(j) = x(indexz);
yz(j) = y(indexz);
zz(j) = z(indexz);
end
hold on
% plot the x-z curve that was just calculated
plot3(xz,yz,zz,'g--')
end
% plot the x-y curves
for i = 1:k
    if (i==1)
        index=1;
    else
        index = (i-1) * (m+1) + 1;
    end
    xy(i) = x(index);
    yy(i) = y(index);
    zy(i) = z(index);
end
%plot3(xy,yy,zy,'r--')
hold off

```

```

% reflector_rays.m
%
% This program is a two-dimensional calculation (x-y plane) of the
% ideal shape of the solar water heater reflectors for TransTech Industries
% (Dakar, Senegal). The size of the surface is also calculated, by
% determining where the extreme minimum and maximum altitude light rays hit
% the x-axis (for a tank with a horizontal surface) and the y-axis (for a
% tank with a vertical surface). The path of the extreme light rays are
% also plotted on the graph for visual inspection.
%
% Written by Robin Liu (robinliu@alumni.princeton.edu) and Francis Joseph
% Mills IV (f-mills@alumni.northwestern.edu); interns for Engineers for a
% Sustainable World and ONG CRESP- Senegal; 25 August 2004

% set parameters
k = 5000;
deltay=0.01;

%set initial conditions
x0=25;
y0=50;

%average incoming angle
theta = 40*(pi/180);
alpha = (pi/2) - theta;
%maximum incoming angle
phi = theta + (34*(pi/180));
%minimum incoming angle
delta = theta - (35*(pi/180));

%calculate constants
D = phi - theta;
E = theta - delta;

%calculate initial values
x(1)=x0;
y(1)=y0;
slope(1)=-tan(0.5*(((pi/2) - theta) - atan(x(1)/y(1))));

for i = 2:k
    x(i)= x(i-1) + (slope(i-1) * deltay); % calculate x
    y(i)= y(i-1) + deltay; % increment y
    slope(i)= -tan(0.5*(((pi/2) - theta) - atan(x(i)/y(i)))); %calculate slope
    % calculate x-min (where the minimum altitude light ray hits the
    % x-axis
    x_min(i) = x(i)-(y(i)*tan(atan((x(i)/y(i))) + E));
    % calculate x-max (where the maximum altitude light ray hits the
    % x-axis
    x_max(i) = x(i) - (y(i)*tan(atan((x(i)/y(i))) - D));
    % calculate y-min (where the maximum altitude light ray hits the
    % y-axis
    y_min(i) = y(i)-(x(i)/(tan(atan((x(i)/y(i))) - D)));
    % calculate y-min (where the minimum altitude light ray hits the
    % y-axis
    y_max(i) = y(i) - (x(i)/(tan(atan((x(i)/y(i))) + E)));
end

%initialize min and max values
minx = 0;

```

```

maxx = 0;
miny = 0;
maxy = 0;

% for loop to determine the actual maximum and minimum x and y values
for j=2:k
    if x_min(j) < minx
        minx = x_min(j);
    else
        minx = minx;
    end
    if maxx < x_max(j)
        maxx = x_max(j);
    else
        maxx = maxx;
    end
    if y_min(j) < miny
        miny = y_min(j);
    else
        miny = miny;
    end
    if maxy < y_max(j);
        maxy = y_max(j);
    else
        maxy = maxy;
    end
end

%-----
%loop for generating 2D light projections
%-----
xlightlimit = -2;
ylightlimit = 0;

numberlightrays = 11; %number of light rays to be used
lineindex = 1; %initialize the light ray variable
hold off
for lightrays = 1:numberlightrays

    %construct and plot average light rays
    xpoint(1)=xlightlimit;
    ypoint(1)=y(lineindex)+(((x(lineindex)-(xlightlimit))*tan(theta)));
    xpoint(2)= x(lineindex);
    ypoint(2)=y(lineindex);
    ypoint(3)=ylightlimit;
    xpoint(3)=x(lineindex)-(tan(((pi/2)-theta) -2*atan(-slope(lineindex))))*(y(lineindex)-ylightlimit));
    plot(xpoint,ypoint,'m--');

    %construct and plot highest (maximum angle phi) light rays
    xhighpoint(1)=xlightlimit;
    yhighpoint(1)=y(lineindex)+(((x(lineindex)-(xlightlimit))*tan(phi)));
    xhighpoint(2)= x(lineindex);
    yhighpoint(2)=y(lineindex);
    yhighpoint(3)=ylightlimit;
    xhighpoint(3)=x(lineindex)-(tan(((pi/2)-phi) -2*atan(-slope(lineindex))))*(y(lineindex)-ylightlimit));
    plot(xhighpoint,yhighpoint,'g-.');

    %construct and plot lowest (minimum angle delta) light rays
    xlowpoint(1)=xlightlimit;
    ylowpoint(1)=y(lineindex)+(((x(lineindex)-(xlightlimit))*tan(delta)));

```

```

xlowpoint(2)= x(lineindex);
ylowpoint(2)=y(lineindex);
ylowpoint(3)=ylightlimit;
xlowpoint(3)=x(lineindex)-(tan((((pi/2)-delta) -2*atan(-slope(lineindex))))*(y(lineindex)-ylightlimit));
plot(xlowpoint,ylowpoint,'b:');

hold on

lineindex = lightrays*(k/(numberlightrays-1));
end
% plot the actual reflector shape
plot(x,y,'r-')
axis equal;
v=axis;
line ([v(1),v(2)],[0,0])
hold off

```

E.5 Sun Angle and Azimuth Data

The following data is taken from the website

<http://aa.usno.navy.mil/data/docs/AltAz.html>, using an average latitude of 14°N and average longitude of 14°W for Senegal, and GMT.

	December 1		January 1		February 1		March 1	
	Angle	Azimuth	Angle	Azimuth	Angle	Azimuth	Angle	Azimuth
12:00	52.4°	162.7°	50.2°	158.4°	54.4°	150.7°	62.8°	140.5°
13:00	53.9°	185.8°	53°	180.3°	58.7°	175.6°	68.6°	174.4°
14:00	49.7°	207.4°	50.1°	202°	56.4°	202.2°	65.1°	211.8°
15:00	41.2°	223.2°	42.7°	219°	48.6°	222°	55°	234.2°
16:00	30.3°	233.8°	32.4°	230.6°	37.7°	234.8°	42.4°	246.2°
17:00	18°	241°	20.5°	238.4°	25.2°	243.1°	28.7°	253.4°
18:00	5.1°	245.9°	7.8°	243.9°	11.9°	248.7°	14.6°	258.5°
19:00							0.7°	262.5°
	April 1		May 1					
	Angle	Azimuth	Angle	Azimuth				
12:00	72.6°	120.6°	77.1°	82.7°				
13:00	80.8°	180.4°	87.9°	307.4°				
14:00	72.5°	239.7°	73.8°	276.7°				
15:00	59°	255.7°	59.3°	276.5°				
16:00	44.7°	262.9°	44.9°	277.8°				
17:00	30.2°	267.5°	30.5°	279.8°				
18:00	15.7°	271.2°	16.2°	282.2°				
19:00	1.5°	274.8°	2.3°	285.3°				

To calculate the average angle (θ), the average of the altitude at 13:00, when the sun is at its highest point in the sky, was taken for the 6 months and also for December to March, when the water heating is the most important. Using these two averages, weighting it more for the earlier months, θ is calculated to be 60° from the horizon. The maximum angle is then found from the data set and this is taken as ϕ , the extreme maximum altitude. Similarly, the minimum altitude is found from the data set and is the value of δ , the extreme minimum altitude. The resulting values are given below:

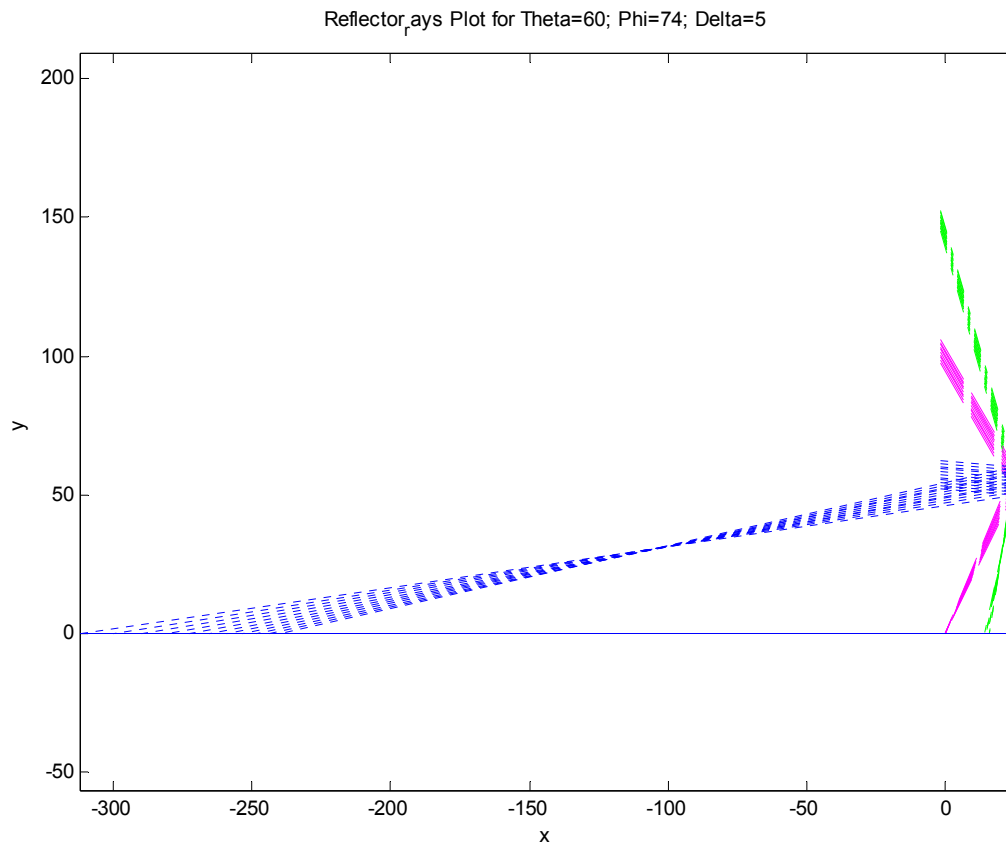
	Absolute Altitude	Altitude in relation to θ
θ	60°	0°
ϕ	74°	+14°
δ	5°	-55°

The same method is used to calculate the average azimuth (α). The average of all the azimuth data shown above is calculated, along with the values between 14:00 to 18:00, when the heating is most important. Using these two averages, weighting it more for the desired hours, α is calculated to be 235° from north. The maximum azimuth is then found from the data set, and taken to be β , the extreme maximum azimuth. Similarly, the minimum azimuth is found

from the data set and taken to be γ , the extreme minimum azimuth. The resulting values are given below:

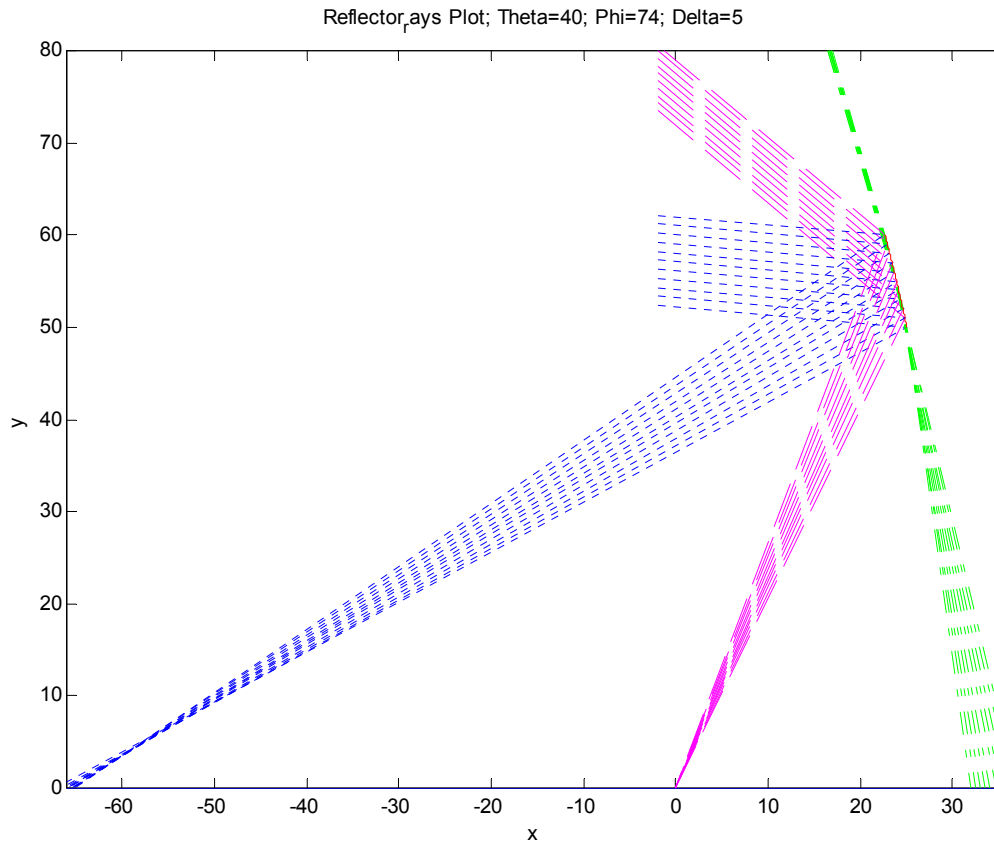
	Absolute Azimuth	Azimuth in relation to α
α	235°	0°
β	308°	+73°
γ	83°	-152°

E.6 Sample MatLab Figures



Initial Conditions : $x_0 = 25$
 $y_0 = 50$

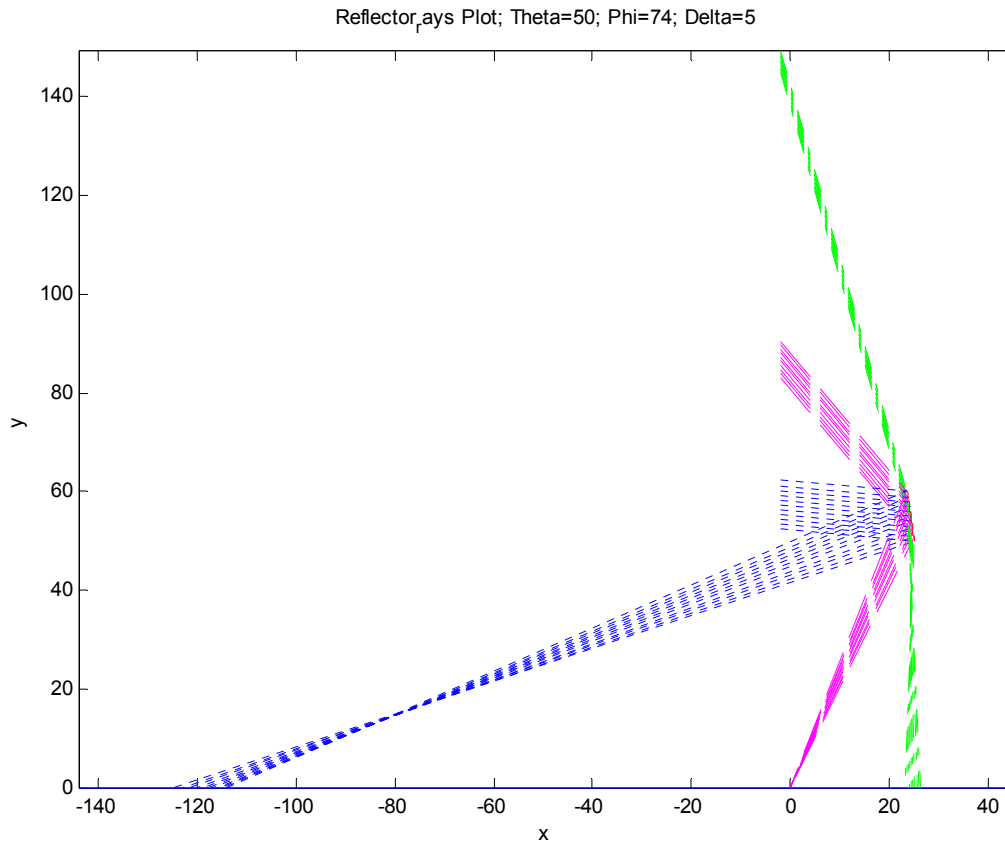
minimum $x = -312.0468$
maximum $x = 15.8396$
minimum $y = -109.6705$
maximum $y = 54.4311$



Initial Conditions : $x_0 = 25$
 $y_0 = 50$

minimum $x = -67.3340$
maximum $x = 36.8480$
minimum $y = 0$
maximum $y = 44.5303$

This graph has problems because the maximum altitude light rays go through the reflector surface and are concentrated behind it, which is not possible.



Initial Conditions : $x_0 = 25$
 $y_0 = 50$

minimum $x = -124.9818$
maximum $x = 26.2445$
minimum $y = -4.2256e+005$
maximum $y = 49.7163$

This graph has problems because the maximum altitude light rays go through the reflector surface and are concentrated behind it, which is not possible.

Initial Conditions : $x_0 = 25$; $y_0 = 50$; $z_0 = 0$

