QUEEN'S UNIVERSITY

APSC 381

Solar Cooker for the Developing World

Group 19

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Executive Summary

The objective of the project was to design a solar cooker that could take the available solar energy and cook food in a developing country. The solar cooker was designed to be affordable for the populations of Mali, Africa. It had to be durable for the intense heat and weather conditions, and must provide an effective alternative to current fuel sources for cooking food. It was determined that a box cooker would be the most effective solution to cooking food in Mali. A box cooker is used to trap radiant heat and use natural convection inside the box to thoroughly cook the food.

The final design of the solar cooker was based on an iterative process of using design tools to create designs, and then evaluate them. Weighted evaluation matrices were used to compile the main ideas that were used in preliminary designs. Cost was a large concern and was the most important factor when using the weighted evaluation matrices. When the initial draft was constructed, it was evaluated by a Quality Function Deployment method. Comparing the current design to existing solar cookers revealed what the weak points of the design were. A Failure Modes and Effects Analysis identified the design and process failures that could occur in the current design. The risks were minimized using solutions that lowered the Risk Priority Number of each harmful failure mode.

After the many design tools were applied, a final design was formulated that met all the constraints and functional requirements that were initially outlined by the team. To decrease the heat loss out of the box during the cooking process, multilayered walls were introduced into the design. The walls consist of urethane rigid foam insulation inserted in between two plywood panels, with an interior surface of corrugated aluminum. The corrugated aluminum allows for convective heat transfer through its channels and an overall increased heat transfer to the cooking pot.

Additional sunlight is reflected into the box using three reflective surfaces of Mylar film. The reflectors are mounted by plastic rods, which adjust the angles for different sunlight conditions. The solar energy is transmitted through a transparent cover plate composed of Plexiglas with a low-emissivity film applied to it. The solar energy that enters the cooker gets absorbed by the black aluminum sheeting and emitted as radiation to the pot.

The cooker was engineered as a compact design that can be folded easily into a wooden box for transport. The cooker was estimated to weigh 22.7 kg and can be carried by handles on the side walls. The final cost estimation, excluding manufacturing and distribution costs was $22.44.

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1.0 Introduction & Objective

The design team was tasked with designing a solar cooker which was targeted at users in the developing world. Many areas of the world have abundant solar energy which could be harnessed to cook for free. The savings in fuel costs are estimated to be great enough for a solar cooker to be economically feasible. The solar cooker must be inexpensive, safe, portable, durable and easy to use.

To date, the group has done extensive research on solar cookers, using existing solar cooker design ideas as well as original ideas which were developed in idea trigger sessions. A design for a solar cooker was created based on results from morphological charting, weighted evaluation matrices, and Quality Function Deployment. From these results, a CAD model of the design was created. Once the group had a design, material cost estimates were made and a Failure Mode and Effects Analysis of the design was conducted.

This report marks the end of product development. Continuation of the project beyond this point would involve constructing and testing a prototype, developing an economical manufacturing method, and developing a distribution strategy. If this process could be repeated, a number of different procedures would be adopted. Specific details on these subjects can be found in later sections of the report.

2.0 Background Information & Theory

Within the confines of the Tropic of Capricorn and the Tropic of Cancer, the sun provides a reliable, powerful and very valuable energy resource. Solar cooking is an inexpensive, environmentally friendly and health safe alternative for the 1.5 billion people who do not have access to electricity in developing worlds and rely predominantly on open fires for cooking (UNDP, 2009). Wood, charcoal and to a lesser extent dung are used for fuels. These fuels cause dangerous air pollutants when burned, and have been linked to the annual deaths of almost two million people from pneumonia, chronic lung disease, and lung cancer (UNPD, 2009). The share of people without electricity is shown in Figure 1. This shows the potential a solar cooker has for developing countries, especially in sub-Saharan Africa.

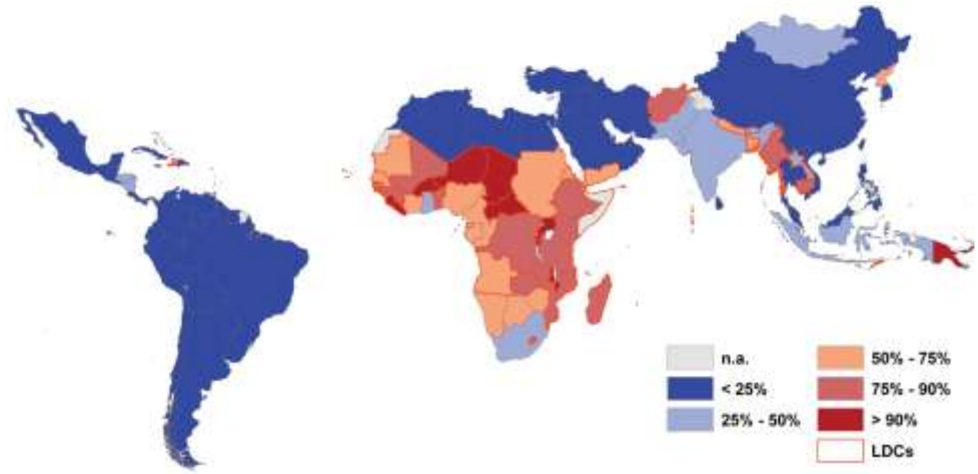

Figure 1: Share of people without electricity access for developing countries, 2008 (UNPD, 2009)

On average, annual solar power is equal to more than 6kWh energy per square meter a day in countries located near the equator (SCIDEV, 2005). In some areas of the average number of sunny days annually is as high as 325. This is shown in Figure 2, a map of the world with annual average solar radiation (SCI, 2005). This solar radiation can be converted to heat with a solar cooker.

Solar cooking is not a new technology; solar cookers have been introduced into many developing countries in many different forms, some which are written about in this report in the Background section. Despite these existing designs, the abundance of solar energy in the many developing countries can be used to create a better way of living, a relatively untapped resource.

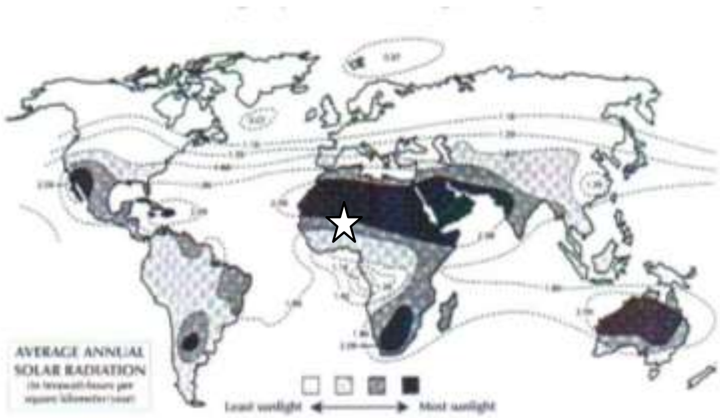

Figure 2: The average annual solar radiation expressed in terawatt-hours per square kilometer per year (SCI, 2005)

To focus the design for the solar cooker, a target group was used to determine specific cultural and social requirements for a smaller populace. Mali, Africa was chosen as a focus group due to the availability of abundant solar energy and the poverty that controls the nation. The star locates Mali on Figure 2. It is landlocked and partially covered by the Saharan Desert. The people of Mali have a poor standard of living as evidenced by their Human Development Index, HDI. HDI is a way to measure human development, including factors: living a long and healthy life (measured by life expectancy), being educated (measured by adult literacy and enrolment in school), and having a decent standard of living (measured by purchasing power parity, individual's income). In 2007 Mali had a recorded HDI value of 0.371, which gave the country a ranking of 178 out of 182 countries with data. In comparison Canada was forth with an HDI value of 0.966, and Norway lead the way with 0.971. 63.8% of Malians live below the national poverty line, living on less than $2 US a day (HDRSTATS, 2008). About 68% of Malians are rural, living off the land and the Niger River (CIA, 2009). Since such a high proportion of the Malian population live in rural settings each home would have room for a solar cooker to place outside of their dwelling in combination with traditional wood burning means.

Firewood has become very expensive and some families will spend up to a third of their earnings to buy firewood or walk kilometers to gather wood (SCI, 2004). Environmentally and economically, firewood does more harm than good. It causes health problems: burns, eye disorders, pneumonia, and lung diseases (Women's International, 1998). Using a solar cooker would increase time available to the cook in the area and save money due to less fuel expenses. Minimal maintenance is needed to cook the food because temperatures are low enough to prevent burning. This is a valuable tool as the solar cooker does not require constant attention. Conversely, cooking on an open flame requires constant supervision because temperatures are much higher causing food to burn easily and the fire must be maintained. Consequently the solar cooker provides the cook with more available time compared to cooking on an open flame. This is very time consuming especially considering that the cook had to gather firewood. The extra time allows the cook to do other chores or new projects that could bring in extra money to the family. The extra money can be used to buy more nutrient rich foods and help finance the family's needs.

The Malians base their diet on what they can grow locally and what they can buy. This includes: cereals (maïze, sorghum, rice, wheat and bread,) legumes (groundnuts, cowpeas and bambara groundnuts,) oil and sugar (sugar, honey, and groundnut oil), fruits (lemon, baobab pulp, and dates), vegetables (onions, okra, tomatoes, hot peppers, pumpkin, sweet potato, yam, sweet peppers, cabbage and cassava), some meat (beef, mutton, and fish), and milk and eggs. These foods are generally wet-cooked, in a process very similar to a slow cooker. If the sun conditions are right the solar cooker has the same capabilities as a modern slow cooker, consistent temperatures around 80°C (Food Safety and Inspection, USDA). Cooking times vary depending on the type of food, but it is expected that a solar cooker will require approximately twice as much time for cooking as an open flame. Typical cooking times for a variety of common food can be seen in Table 1

Table 1: Average cooking times for 2kg of the most common foods in Africa (fot, 2007)

1 - 2 Hours	3 - 4 Hours	5 - 8 Hours
egg	potatoes	large roasts
rice	root vegetables	soup and stew
fruit	some beans, lentils	most dried beans
above ground vegetables	most meats	
fish	bread	
chicken		

In many developing countries unsafe drinking water is common cause of illness and death, and a significant contributor to general poor health. By providing a way to pasteurize water without the need for wood or gas is a powerful tool. Water needs to reach 65°C and remain at that heat for five minutes to kill 99% of disease carrying bacteria (SCI, Water Pasteurization). The different temperatures needed for common bacteria are included in Table .

Table 2: Temperatures needed to kill disease carrying bacteria (SCI, 2005)

Microbe	Killed Rapidly At
Worms, Protozoa cysts *(Giardia, Cryptosporidium, Entamoeba)*	55°C (131°F)
Bacteria *(V. cholerae, E. coli, Shigella, Salmonella typhi)*, Rotavirus	60°C (140°F)
Hepatitis A virus	65°C (149°F)
(Significant inactivation of these microbes actually starts at about 5°C (9°F) below these temperatures, although it may take a couple of minutes at the lower temperature to obtain 90 percent inactivation.)	

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Mirror Reflectance:

Many solar cooker designs increase collection of sunlight by using arrays of mirrors. Mirrors can be separated into three categories: flat, parabolic and Fresnel. These mirror types can be seen in Figure 3. Parabolic mirrors allow light to be focused on a very small target area, but are more expensive due to the cost of manufacturing the curved surface. Flat mirrors are cheaper to manufacture, but are not good at channeling light and require a larger target area. Fresnel mirrors form a compromise between flat and parabolic mirrors. These mirrors are a series of thin, flat mirrors which are each tilted to a slightly different angle to concentrate light without requiring a curved surface. The surface area of the mirror is proportional to the energy lost during reflection, so a flat mirror would have the least energy lost relative to reflection because of its smaller area.

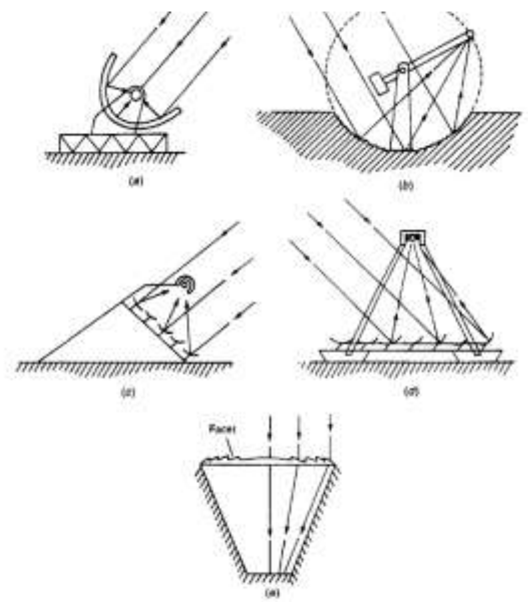

Figure 3: Solar Concentrator types: (a) parabolic; (b) circular with tracking absorber; (c) and (d) Fresnel mirrors; (e) Fresnel lens (Cleveland, 2004)

Due to the movement of the sun, mirrors may be required to rotate to track the sun. The mirror only needs to move if it is not concentrating its light on the target area, so a larger target area and tighter focus are preferred.

Mirror efficiency can be calculated from Equation (1), where ρ_m is the reflectance of the surface, τ_c is the transmittance of light through any surfaces between the sun and the mirror, α_r is the receiver surface absorption, δ is an error factor accounting for tracking and surface errors and *F(i)* is the fraction of reflected solar flux intercepted by the receiver (assumed to be 100% of solar flux). (Cleveland, 2004)

$$\eta_0 = \rho_m \tau_c \alpha_r \int \delta F(i) \quad (1)$$

Absorption Surfaces:

In order to harvest energy from the sun, the solar cooker must have a surface which converts as much UV radiation as possible to heat. Absorptance and emittance for common surfaces are tabulated in Incropera, 2007. These values are used to calculate energy absorbed by the surface using Equation (2) where A is area, σ is the Stephan-Boltzmann constant, α is absorptance, ε is the emittance, T_S is the temperature of the sun, T is the temperature of the surface and T_a is the ambient temperature of the surroundings. (Incropera, 2007)

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$$Q = A\sigma \times [\alpha(T_S^4 - T^4) - \varepsilon(T^4 - T_a^4)] \quad (2)$$

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Heat Transfer:

Heat must be transferred to the food from the absorption surface. Transfer occurs by different mechanisms depending on the solar cooker type. For concentration cookers, this transfer occurs purely by conduction. For box cookers, heat is transferred through a medium such as air to the food by a mechanism known as convection. In addition, box cookers must attempt to reduce conduction from the absorption surface to the walls of the box to reduce heat loss to the surroundings.

Conduction:

Conduction is the flow of heat through a solid along a temperature gradient. In this case, the temperature difference between two points is directly related to the heat flow between those points. This type of heat flow is modeled by Equation (3), where k is the thermal conductivity. Thermal conductivity is tabulated for common materials. However, the heat flow over the contact area between two solids is difficult to predict, so heat flow through a wall with many layers can only be approximated.

$$q = kA\frac{dT}{dx} \quad (3)$$

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Internal Convection:

For a box cooker, heat must be transferred from the heated bottom plate of the box to the air. This process is known as natural (as opposed to forced) convection. Equations (4 and 5) model the convective heat transfer coefficient h for different surfaces of a box heated from the bottom surface and heated from the top surface. L refers to the surface length in the direction of fluid flow, T_1 refers to the bottom surface temperature and T_2 refers to the top surface temperature. The convective heat transfer coefficient can be used to model convective heat flow as seen in Equation (6) where T_∞ refers to the bulk fluid temperature, and T_s refers to the hot surface temperature. Pr, the thermal conductivity k, the kinematic viscosity ν, and parameters α and β are tabulated for different fluids at a range of operating temperatures.

$$For\ the\ Walls,\quad \mathrm{h} = \frac{k}{L}\left\{0.825 + \frac{0.387}{[1+(0.492/\mathrm{Pr})^{9/16}]^{4/9}}\left(\frac{g\beta(T_1 - T_2)L^3}{\alpha\nu}\right)^{1/6}\right\}^2 \quad (4)$$

$$For\ the\ top\ and\ bottom\ plates,\quad \mathrm{h} = 0.15k\left(\frac{g\beta(T_1 - T_2)}{\alpha\nu}\right)^{1/3} \quad (5)$$

$$Q = \mathrm{hA}(T_s - T_\infty) \quad (6)$$

External Heat Transfer:

Modeling heat lost from the outside of the box to the surrounding air is done using Equation (7) to find h for fluid flowing across a flat plate.

$$\mathrm{h} = 0.664kPr^{1/3}\left(\frac{V}{\nu}\right)^{1/2} \quad (7)$$

Types of Solar Cookers

Solar cookers come in various forms, utilizing solar energy in different ways. Figure 4~~Figure 4~~ shows a classification chart for the various types.

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After initial research into using latent heat storage methods, it was quickly determined that they would not be a feasible for the design. This is because of the phase change to a liquid involved which would have required the phase change material (PCM) to be completely airtight to prevent degradation and contamination into the cooking volume. Also, some of the PCMs had varying degrees of toxicity and it was agreed that having them in proximity to food would not be acceptable.

The indirect cooking methods were also not ideal for the design due to their higher complexity associated with have multiple parts and in some cases piping between the solar collection area and the cooking area.

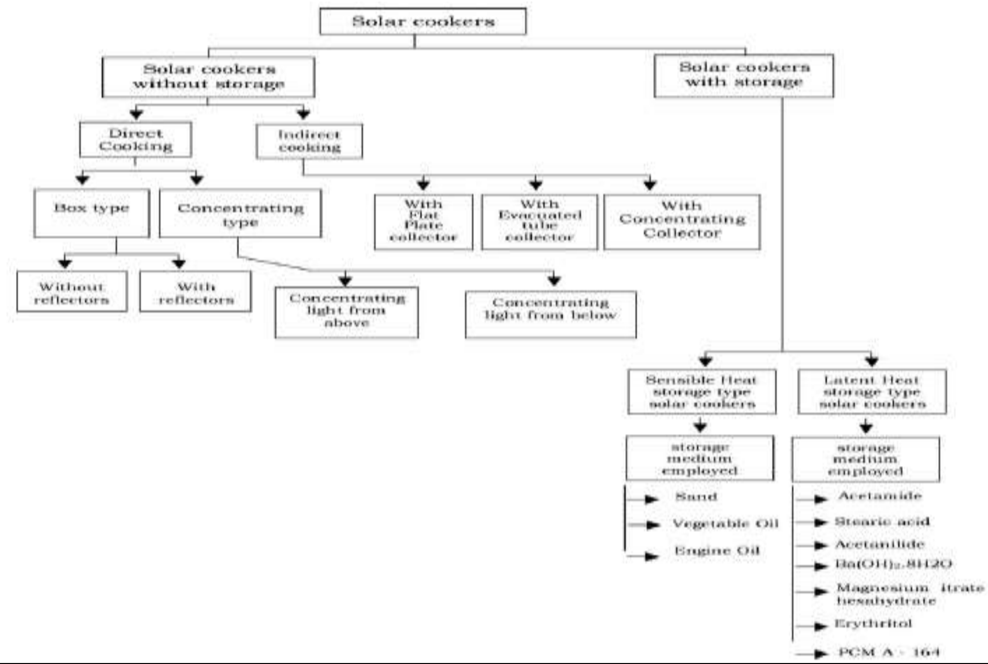

Figure 4: Classification of Solar Cookers(Sharma, 2009)

Concentrating Type

Concentrating solar cookers direct solar energy onto small target areas to cook food. This is achieved by using mirrors of various types to focus light at a specific point. The cooking utensil is placed at this focus point. Depending on the design, concentrating cookers can reach temperatures of 300ºC (Sharma, 2009) Concentrating cookers can use multi-paned, Fresnel, spherical or parabolic mirrors to attain these high temperatures.

Though concentrating cookers can reach high temperature and have short heat up times they have a high risks for burns and fires, they are complex and costly to design and construct. Concentrating solar cookers require frequent adjustments and tracking of the sun to maintain an optimal focus of solar energy.

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Figure 5: Concentrating type cooker: (a) panel cooker, (b) funnel cooker, (c) spherical reflector, (d) parabolic reflector, (e) Fresnel concentrator and (f) cylindro-parabolic concentrator (Sharma, 2009)

<u>Box</u>

Box solar cookers are insulated containers that have a clear cover to let in light from the sun. The cooker traps solar radiation inside much like the greenhouse effect. The box may also have insulation to better withhold heat. The interior and the cooking pot are painted black to convert light into radiation; this heat is then convectively circulated throughout the box. Mirrors can also be used in order to increase the effective area of the box cooker and increase the amount of solar energy entering the cooking volume. Higher temperatures are reached with reflective surfaces used. The cooker showcased in **Error! Reference source not found.Error! Reference source not found.**f can reach temperatures up to 225ºC (Sharma, 2009).

Box cookers do not achieve temperatures as high as concentrating cookers, around 100ºC (Sharma, 2009) but this temperature is sufficient for slow cooking and pasteurizing water. Box cookers are simpler to operate, require less frequent directional adjustment and have less complex construction. Mirror arrangements of box cookers involve flat mirrors as opposed to curved for parabolic concentration cookers. They have a lower risk of burns and no risk for fire due to the temperature being spread throughout the box. They can also cook a greater amount of food at one time. Conversely, the low temperature leads to an extended cooking time.

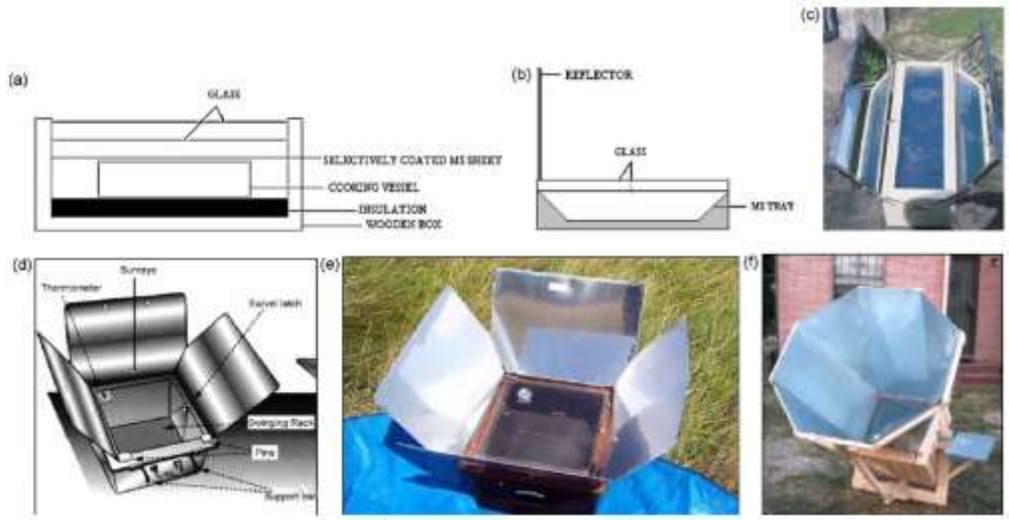

Figure 6: Box type cooker: (a) without reflector, (b) with single reflectors, (c) with double reflectors, (d) with three reflectors, (e) with four reflectors and (f) with eight reflectors. (Sharma, 2009)

Hybrid

The CooKit Solar Cooker is a hybrid design that takes elements from both box and concentration categories. A matte black pot is placed inside a bag which traps heat. The bag is then placed in the center of aluminum lined cardboard reflectors which focuses light into the centre. The CooKit is simple and inexpensive, costing only $17.50 (SCI, 2009). Hybrid designs such as the CooKit, that are constructed from cardboard, are less durable and have a smaller cooking area.

3.0 Discussion

3.1 Problem Definition

People living in developing countries make very little money, many living in poverty. To cook their food they use firewood, kerosene or charcoal spending up to a third of the money they make. The sun is an inexpensive, environmentally friendly and healthy safe option. The objective was to create a solar cooker design which suits their needs and easily be distributed in developing countries.

Design an effective solar cooker that can reach a safe cooking temperature in a reasonable amount of time. It needs to be inexpensive, safe, portable, durable, and easy to use.

Constraints:

Price Constraint: the cooker must be similar to the cost of designs with which it will be competing. In addition, the price of the cooker must not exceed the yearly cost of cooking fuel.

Thermal Constraint: the cooker must exceed a temperature of 65 ^{o}C in order to pasteurize water.

Durability Constraint: The cooker should be intended to last for ten years, and should be expected to pass standard tests from the Indian Bureau of Standards for Solar Cookers.

Volume Constraint: The cooker should be able to hold three pots each having a volume of 2 liters.

Weight Constraint: The cooker should not weigh more than 50 lbs.

Ease of Use: The cooker should not require written instructions for use and should be able to be operated safely.

3.2 Design Process

First Constraints

Over the course of the design process, the problem definition and the constraints evolved constantly, culminating in the final form seen in this report. Originally, the target population was not specified, and constraints were not qualitative. The constraints developed early in the design process were: the solar cooker must be safe, affordable, durable, sustainable, easy to use, and portable. After conducting the background research described earlier in the report, Mali, Africa was chosen as our target population.

Morphological Chart

The group organized ideas in a morphological chart, referred to as the morph chart for the rest of this report. The morph chart was not used for all the elements of the solar cooker. Rather, this method was applied to situations where the best option was not obvious.

Different design options and material choices were put into categories based on the complexity of the idea as well as the functional requirement which the design option or material choice addresses. Complexity of each selection was qualitatively evaluated based on how difficult it would be to manufacture and assemble, as well as how many moving parts were required. For example, a parabolic mirror would have a high complexity but would address the requirement that the solar cooker have adequate collection area.

Making a morph chart served two purposes. First, the group was able to evaluate what different design ideas were possible and discuss different combinations of cooker elements that would make a good cooker. Second, the group was able to identify complex elements, and decide whether the complexity was worth the additional value.

When complex design options were determined to be valuable, attempts were made to simplify them. By using a morph chart, the group was able to identify which design options needed more insight and in this way the time and resources of the group were focused more effectively.

The morphological chart, seen in its entirety in Appendix A1, addressed the following elements of the design: support system to move the cooker, radiation-to-convection interface, insulation, cooking space access, reflector mounting, reflector material, and base material. These different features were then compared with the help of a weighted evaluation matrix.

First Weighted Evaluation Matrix

The weighted evaluation matrix, referred to in this report as the WEM, took all of the elements' features from the morphological chart and evaluated them based on a set of weighted criteria. This was the group's first of two weighted evaluation matrices which can be seen in Appendix A2. The categories and weightings for this WEM can be seen in Table 3. The thermal capabilities, safety and cost were identified as being the most important customer requirements. In addition, ease of use, durability and assembly were also identified as customer requirements. This WEM provided the group with a basis to create the preliminary design. The elements with the highest results were chosen as parts to the design. The preliminary design can be seen in Figure 7, with other initial drawings shown in Appendix A3.

Table 3: The first WEM's weightings, showing the importance of the thermal capabilities, safety and cost.

Customer Requirement	Weight
Thermal Capability	30
Safety	25
Cost	20
Ease of Use	10
Durability	10
Assembly	5
TOTAL	100

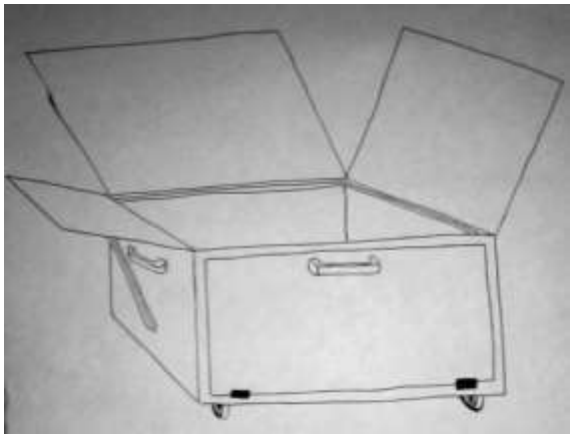

Figure 7: Preliminary Design as determined by the first WEM

Preliminary Design

The preliminary design had four wheels that could rotate 360°; the wheels would allow the cook to move the solar cooker in and out of the house easily but the wheels were very expensive. The inside surface had rounded corners which encouraged efficient convection. Styrofoam was rated the highest in the WEM therefore it was used in the preliminary design. To access the food the oven door technique received the highest mark due to its thermal capabilities and safety aspects. When the oven door was opened less hot air escaped and the cook would not have to remove any hot pieces like the transparent pane. The mirror arrangement with three mirrors hinged from the top was rated the highest due to its higher ranking in five of the six categories especially for its simplicity. The cover plate was determined to be Plexiglas due to its higher ratings in safety and cost.

The initial preliminary design price was estimated at about 100$. Expenses are expanded in detail in the Economics section of the report. The price was too high to sell in Mali or any similar developing country. The solar cooker was also going to be expensive to manufacture due to the high number of parts. Therefore the group used additional design processes to streamline the design. The group created a goal to drop expenses by simplifying the design and finding materials that were inexpensive yet appropriate for a harsh arid environment and durable for long term use.

Redefining of the Constraints

Based on experience with the preliminary design, the constraints of the solar cooker needed to be redefined. The initial constraints for the preliminary design were vague and did not provide precise specifications. By defining the constraints more precisely the group was able to focus on the target group's needs and define which different aspects of the preliminary design would need to be improved. In particular, a specific price target was set. This set of constraints is mentioned in the Problem Definition.

Reverse Engineering and TRIZ

Once the constraints had been redefined, the next step was to take apart the preliminary design piece by piece in order to reverse engineer the initial design. Since the number of parts and machining necessary to create the solar cooker increased the total cost, determining what parts were necessary and weaknesses in the others allowed the team to create a better design.

While looking at the different parts of the solar cooker the team looked at TRIZ. Each part was compared to different improving and worsening features to continue to streamline the design and determine the solar cooker`s strengths.

- The weight of the stationary object was an improving feature that was compared to stability and strength in TRIZ. The design had to be light enough to move easily but strong enough to withstand the wind.
- Principle 3: Local quality was considered; make each part of the solar cooker function in the best conditions for its operation.
- Reliability and ease of repair are two very important aspects to the solar cooker design that were determined important. In TRIZ these were used as improving features using Principle 26: Copying, to use simplification and inexpensive parts, and Principle 34: Discarding and recovering, to think about how the solar cooker can be repaired easily. The solar cooker must be reliable to provide a consistent cooking apparatus. When a solar cooker is damaged an easy way to repair it must be available to the local people. Simplifying the design helps make repair easier because there are less parts and the remaining parts can be repaired or replaced easily. The materials are discussed further in the Idea Development section of the report.

In addition to TRIZ, reverse engineering was done to find ways to reduce cost and weight. This was done primarily by reducing the amount of metal and glass used. As a result, it was decided that the box would be built out of wood instead of metal. In addition, aluminum mirrors would be replaced with Mylar sheets supported by thin sheets of plywood. The support system for the mirrors was also changed from machined metal parts to wooden parts. Insulation was reduced by removing the layer on the bottom of the box. In addition, wheels were removed in favour of a stronger box structure which could be dragged or lifted by handles attached to the sides of the box.

Second Weighted Evaluation Matrix

For the preliminary design a weighted evaluation matrix was used to evaluate the solar cooker design. After the design had been streamlined, and the weightings on the matrix were changed, so the parts were evaluated again. The new weightings for the WEM can be seen in Table 4. The weighted evaluation matrix can be seen in Appendix A4 comparing different parts for the solar cooker design.

Table 4: The second WEM's weightings, showing the importance of cost.

Customer Requirement	Weight
Cost	40
Thermal Capability	20
Safety	15
Ease of Use	10
Durability	10
Assembly	5
TOTAL	100

The weightings needed to be changed because the cost weighting was too low. The price sensitivity of the user was determined by talking to an NGO that works in Africa and provided information about solar cooking projects currently operational there. Almost 64% are living below the poverty line which means they make under $2.00 a day (SCI, 2007). With an income so low, the cost of the solar cooker was the most important requirement for the intended consumer group.

If the people were going to spend their hard earned money to buy a solar cooker, the thermal capabilities must provide comparable results to that of a fire. The safety of the solar cooker was important to the group. People in developing countries have already been exposed to poor air conditions and receive burns due to firewood cooking. The team wanted to provide a design that would not cause any harm to the cook or the people that ate the food prepared in the cooker. Ease of use is important to new cooks because they do not want any lag in their cooking abilities. Users should not be prevented from cooking because the solar cooker was too difficult or temperamental to use. Solar cookers must last for a minimum of ten years (Indian Standard, 1999). The assembly of the cooker was considered less important due to the possibility of pre-assembly and the more importance to the other requirements.

Because of the change in the weightings, there were different features that were better suited to what the target population required. For transportation, handles had a higher total because of the lower cost and durability. The inside surface with 90° corners received higher marks in all but thermal capabilities so was changed in our design. Straw and Styrofoam insulation were rated the same in the WEM. The group felt that straw was a liability to the design because it is not suitable for the situations it would be put in, deteriorating and rotting easily with the addition of moisture. , but the results were very close to each other, 322.5 and 317.5 respectively. The team felt that the oven door access was more innovative and provided a safer option to the cook using the solar cooker. The mirrors assembly would stay the same with three mirrors hinged to the top, and the transparent cover plate would also stay the same as Plexiglas. Further design details are discussed in Idea Development.

Quality Function Deployment

A Quality Function Deployment Matrix, or QFD, was used to compare solar cookers currently used in developing countries to the team's solar cooker. Two different types of solar cookers were used to compare to the team's design. The first of these was an inexpensive parabolic option, and the second was the inexpensive CooKit, the most popular option available in developing countries, against the team`s solar cooker design. In Appendix A5 the QFD shows that the CooKit was the best of the three solar cookers with a total of 313 but the team's design had a competing total of 292.

Customer Requirements for the QFD

The Customer Requirements were based off of the constraints that the team developed with the help of the NGO, Solar Cookers International. These requirements include: inexpensive, thermal capabilities, durable, cooker volume, cooker weight, and easy to use.

The **inexpensive** requirement is due to the developing country target group. The cooker cannot be expensive because the target population does not make very much money. The more expensive a solar cooker is the less likely the target population will buy it. The solar cooker cannot cost more than the target population spends on fuel for their cooking fires. The maximum a third of their annual income, $730, so about $243.3 is available to purchase a solar cooker. Though this seems like a lot of money they only make about $2 a day (HDRSTATS, 2008), and this is what keeps cost a very important customer requirement.

The **thermal capabilities** are required to provide a safe cooking temperature that will kill 99% of bacteria in the food and water. As long as the temperature reaches 65°C and maintains that temperature for five minutes, 99% of the bacteria is killed, which was mentioned in the Background section of the report. This ensures that the cooker cooks food at a safe temperature.

Durability is a user requirement that includes material durability, thermal integrity, and life span of the cooker. There is already a constraint about the life span of solar cookers of 10 years. If people from developing countries are going to spend their money on a solar cooker they expect the cooker to work for a long period of time. Over time solar cookers will experience harsh environmental conditions and user mistreatment, so the cooker needs to be strong enough to withstand such punishment.

The **cooker volume** focuses on how much can fit within the solar cooker. The minimum volume is a small pot but the more the solar cooker can fit makes cooking larger portions much easier. This is an advantage to larger families, or allows different things to be cooked at once, also providing space to pasteurize water all at the same time.

The **cooker weight** is based on the actual weight of the cooker. The cooker needs to be brought in at night to prevent damage from the elements or animal damage, and prevent other people from vandalizing or stealing the cooker. The cooker therefore needs to be light enough to be lifted and moved or the cooker needs another mean to move it, like wheels.

The requirement '**easy to use**' is a combination of how the cooker works, how the cooker is accessed and how fast the cooker cooks/the cooking temperature. The cook wants a cooker that is easy to use so there is no lapse in cooking abilities between fire cooking and solar cooking. This is a concern of many new solar cooks; sometimes cooks will not use the cooker because they cannot get the same results. The cook also requires easy access to the internal compartment that does not cause burns from steam or hot elements of the design. The cooker temperature will make the cooks' job much easier if it is constant and heats quickly.

The Engineering Specifications are the measurable aspect of how the customer requirements will be met. These include: mirror size, box size, manufacturing cost, access to food, material strength, cooking time, assembly cost, and cooking temperature. These specifications are generally self explanatory. The mirror size is based on the area that the mirrors occupy, this includes all mirrored surfaces. The cooker volume is the internal volume, allowing different pot sizes and number of pots. The cooker weight is the mass of the entire cooker. The manufacturing cost is how much the parts of the cooker cost to manufacture. The access to food is more complicated because it includes the access's area to the cooking cavity, the number of barriers between the cook and the cavity, and the reach distance. This is specifically chosen because some cookers are very difficult to successfully use because the cooker is too complicated. The material strength refers to the thermal, stress, strain, and wear strengths of the cooker's parts. The cooking time is the time a cooker takes to heat up to 65°C. Assembly cost is exactly that. The cooker temperature is the maximum average temperature the cooker can maintain.

Failure Mode and Effects Analysis

To determine the hazards of the solar cooker a Failure Mode Effects Analysis, FMEA, was used. The FMEA was a very helpful tool because it made the group aware of problems that had not been noticed before. The analysis can be seen in Appendix A6. In the analysis there were nine areas that showed Risk Priority Numbers, RPN, above 80. The team provided actions to lower the RPN and redesigned the solar cooker to prevent failure. The nine areas included: deterioration in the outer box, deterioration in the insulation, thermal fatigue of the wooden slats, seizure and corrosion in the hinges, cracking of the transparent pane, scratching/ripping of the reflective surfaces, material fatigue in the supports, and corrosion in the screws.

The deterioration occurs due to moisture exposure, so the team took action by prevention. This included staining and sealing the outer box and supports, and providing a vapor barrier for the insulation. If the insulation was left unprotected the heating capabilities of the box would be diminished, preventing the cooker from maintaining a safe internal temperature.

The wooden slats that would have allowed for thermal conductivity were replaced with a corrugated aluminum sheet. The wooden slats were prone to thermal fatigue which would warp, weaken and loosen the slats. This would prevent proper thermal convection, lowering the internal temperature and prevent even heating. The corrugated aluminum would provide a pathway for air circulation and would replace the inner box. This was a way to improve the team's design to make it stronger and provide consistent heat convection.

Before the FMEA, the oven door hinges were directly exposed to the ground. This would have caused dirt grains to enter the hinge tolerance causing seizure. This would have caused reduced or restricted movement in the hinge preventing the cook from using the oven door and therefore also the cooker. The hinges on the oven door required the group to eliminate the seizure hazard by raising the box from the ground. This also helped to lower the RPN value of deterioration in the outer box because the box was no longer directly exposed to the ground.

To prevent corrosion in the hinges and screws the material was changed to contain a chromium alloy. The chromium in the hinges and screws does not oxidize as readily as other alloys. Though this is slightly more expensive, the team could not overlook the magnitude of this RPN. The chromium alloyed hinges and screws are required to maintain the thermal capabilities and the structural stability of the cooker.

The transparent pane is a very important part in the team's design. If the pane were to crack or break due to stress fatigue, thermal fatigue, or from shock the thermal capabilities would drop to zero (if the pane breaks entirely). For prevention the team decided to add a transparent film, this would strengthen the pane, prevent cracks from propagating, and prevent most pane failures from shock.

Scratches from prolonged exposure to sand, dust, grit, and sharp objects to the mirrors prevent reflection and diffuse the reflected solar rays. This decreases the solar cooker's thermal capabilities. A protective film was implemented to prevent scratches on the mirrored surface, lowering the RPN value.

3.3 Idea Generation

Functional elements of a solar cooker were identified from background research. The idea generation phase of this project focused on developing a design which would have all of these functional elements. Design ideas were also intended to meet the requirements of the problem statement in order to produce a solar cooker suitable for the target audience. The functional elements identified included:

- A mechanism to concentrate enough solar energy on a cooking medium to maintain cooking temperature of 65°
- A cooking medium, whose purpose is to convert solar energy to heat and transfer it to food efficiently
- An easily accessible, level surface on which food could be placed during cooking
- A method to allow the cooker to be moved easily

Ideas were developed independently and combined during an idea trigger session. A selection of ideas is listed below, organized by functional element.

<u>Concentrating Mechanism</u>

Ideas for concentrating solar energy all involved using mirrors to increase the amount of sunlight collected. Due to the motion of the sun, some of these designs included methods to move the mirrors independently from the cooker. Pivoting the mirrors came at the cost of an increased number of spare parts and consequently a shorter mean time between failures. All of the designs had to allow for the mirror to be stowed during storage so that the reflective surface could be protected when not in use.

One idea was to have an aluminum framework over which an aluminized Mylar sheet would be spread like a sail. The advantage of this design would be low weight and easy disassembly. The framework could be easily pivoted due to its low weight. However, the design would be fragile. If a member of the framework were to buckle or snap the array would be useless. Also, the sheet could potentially tear or stretch and would be unstable on windy days.

Another idea was to manufacture a set of thin reflective aluminum plates which during storage would lie on top of one another and would be deployed by sliding out in the nature of a fan. This would allow easy storage and transportation of a mirror which in use would expand to cover a wide area.

The simplest idea suggested was simply to have large, flat plate mirrors used on a box-type solar cooker. The mirrors would hinge to the corners of the box and would not move independently from the box. During storage, the mirrors would fold down on top of the box.

<u>Cooking Medium</u>

Cooking mediums are separated between box-type and concentration-type cookers. Designs were intended to convert solar energy as heat, allowing a minimum of dissipation to the environment.

The best idea proposed for a cooking medium for a concentration cooker was a flat, black metal plate. The flat topped plate would serve as a cooking element, and solar energy would be reflected onto the bottom from the mirrors. The plate area exposed to the surrounding air would be minimal, so the lack of insulation would not be a concern. The plate would be made of metal to increase its conductivity and heat capacity. It is important to note that the plate would have to be supported somehow, possibly by a tripod.

Several ideas were proposed for box-type cookers, because of the increased complexity of the heat transfer mechanism in this type of cooker. The following elements are required in order to convert the heat in a box cooker:

- The solar energy must be absorbed and converted to heat
- Convection must be induced to allow efficient transfer of heat to the air
- Conduction through the walls of the box must be avoided

One idea which would serve all of these functions was a set of fins arrayed across the box which would absorb solar energy. These fins would have minimum contact with the box walls and maximum contact with the air. However, the fins would be fragile, expensive and could reduce ease of access to the oven.

Another idea was to have corrugated aluminum or plastic sheet on the walls and floor of the box. The sheet would be painted black to increase absorption of solar energy. The corrugation of the sheet would mean that contact between the sheet and the box wall would be reduced. In addition, natural channels for air flow would form in the corrugations. Food placed on the floor of the box would rest on top of the corrugations without disrupting air flow along the sheet. These are also stronger materials that are more durable.

It was also suggested that the inner surface of the box have rounded corners to reduce areas of stagnant air in the box so that convection would be more efficient. The curved surface would resemble a slow cooker pan and could possibly be removed from the cooker to allow better access to food.

In order to reduce the amount of radiation which could escape the box, a low-emissivity coating was suggested for the transparent pane on top of the cooker. This coating would work on the same principle as a one-way mirror. Solar radiation would pass through the pane into the box but radiation generated in the box would be reflected by the film.

<u>Easily Accessible Cooking Area</u>

Ease of access to food is a concern relevant to box-type cookers. The interior of the box presents hazards similar to an oven. Designs for an oven door must allow easy access to increase safety. At the same time, a minimum of heat should be lost from the box when the door is open.

One idea which maximized accessibility was to have a movable transparent cover plate, which would be detached from the box in order to access food. While this method allowed easy access to food, it also increased the likelihood of wear on the glass. Heat flow was also expected to be a problem if the top surface of the box were removed, as the hot air would quickly rise.

A second idea was to convert one of the walls of the box into an oven door. The door would be hinged to one of the corners of the box and would swing out to allow access to food. This method would not be as conveniently accessible, but heat flow would be reduced and the box interior would still be reasonably accessible.

Another idea was to have a removable baseplate or a baseplate which was only connected to the rest of the box by a hinge. In order to access food, the box would be lifted off the baseplate in its entirety. This method had the best accessibility but would also cause all the hot air to dissipate any time food was accessed.

Finally, it was suggested that if an oven door were used, heat flow could be reduced by placing a curtain inside the box in front of the door. This curtain would restrict the flow of air through the opening while still allowing pots to be placed in the oven.

Easy Mobility

The cooker had to be easy to transport both so that it could be moved to face the sun and so that it could be brought inside when not in use.

It was suggested that if the design were light enough, it could be carried either on one's back or using handles. If it were too heavy to carry, it could be dragged, rolled or disassembled.

One innovative idea allowing easy mobility included turning the box into a wheelbarrow with a handle on one side and two wheels on the other side of the box. This would allow a heavier design to be moved easily. Having a wheelbarrow configuration raised concerns having to do with keeping the cooker level during cooking. The handles would either have to be light or they would shift the center of gravity of the box. Also, it was unlikely that the box would be heavy enough to require this configuration.

Another idea was to mount four shopping-cart wheels to the bottom of the box. This would allow the box to roll while remaining level but is a more expensive option.

3.4 Idea Development

The final design incorporated all the most suitable and effective design features as determined by the various design tools used. The main constraints of the solar cooker were met and the solar cooker can become a functional product. The main constraint in engineering the solar cooker was the cost of the product. Since it was designed for Mali, a developing country, prices needed to be lowered without comprising the quality of the engineering. All the basic elements of the cooker were dimensioned and the most effective materials were chosen for the task they had to perform.

Multi-Layered Walls

The cooker consists of five multilayered walls (including the door) that serve to provide a high resistance to conduction heat loss to the surroundings. The walls consist of four layers of materials as shown by the labeled schematic in Figure 8.

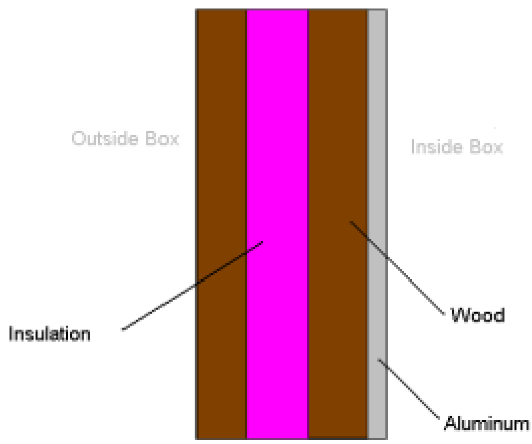

Figure 8: Multi-layered walls of solar cooker final design

The outside surface is made from plywood, a readily available pressure treated wood. The purpose of this outer layer of wood is to prevent conduction through the walls. Conduction is proportional to the thermal conductivity of the materials. Spruce plywood has a tabulated thermal conductivity of 0.12 W/mK at 300K (Incropera, 2007). Including the plywood layer on the outside significantly reduces heat transfer by conduction. The thickness of the plywood is also important for conduction resistance. The thickness of the wood is ½'' (12.7 mm). Although there are many types of wood with exceptional thermal capabilities, plywood is much lighter than hard woods(Table 5). Although plywood is denser than softwood, a more rigid wood was needed to increase the durability of the design.

Table 5: Densities of common woods (Incropera, 2007)

Wood Type	Density (kg/m^3)
Plywood	545
Hardwoods (oak, maple)	720
Softwoods (fir,pine)	510

The second outermost layer of the walls, shown in pink in Figure 8, is the insulation layer. The insulation provides the bulk of the thermal resistance to heat loss out of the box. By incorporating the insulation, the heat transfer out of the cooker is reduced substantially. For quantification behind the placement of insulation and associated heat transfer rates, refer to the Engineering Science section of the report. The insulation chosen was a two-part mixture of Urethane rigid foam. This is a material easily accessible on the market and designed for optimal insulation properties. The approximate thermal conductivity of the insulation is tabulated as 0.026 W/mK at 27 ^{o}C (Incropera, 2007).

A rigid foam insulation was chosen instead of fiberglass because having a more rigid material bolsters the strength of the cooker walls. The outer walls would have to be much thicker to ensure that the large insulation space does not comprise the structural integrity of the walls. Also, fiberglass insulation, although very similar thermal properties, is more expensive (Refer to Engineering Economics section for details).

To protect the insulation from deterioration, the insulation is wrapped in plastic sheeting to seal the insulation from any exposure to moisture. The durability of the insulation was increased substantially by incorporating the plastic seal. The failure mode of the insulation was identified and solved by using the FMEA as described in the Design Process section of the report. The insulation was decided to be ¾''.

The third layer from the outside is composed of plywood, with the same dimensions and properties as the outer panel. The purpose of this layer is to further increase the thermal resistance and also to provide a rigid inner box that screws can be fastened into.

The inside layer is composed of corrugated aluminum. The corrugation is not shown in Figure 8; however, it is a key component for functionality of the solar cooker. The aluminum serves the purpose of absorbing the solar energy that enters the cooker. The absorbing properties of the aluminum are due to the high thermal conductivity value of 237 W/mK at 27 ^{o}C (Incropera, 2007). The surface is painted black to ensure that there is no reflection back out of the box. The corrugations in the metal serve as passageways for fluid movement in the box to induce convection. The more fluid movement, the more random motion of the molecules and hence a greater convective heat transfer. Another purpose of using the aluminum for the inside layer was that it protected the wood from thermal fatigue. The wood could warp under the high temperatures of the cooker, or even worse catch on fire.

Reflective Surfaces

To reflect additional solar energy into the box, reflective Mylar surfaces were incorporated into the final design. Mylar is a thin polyester film that has reflective properties of up to 99% reflectivity. It is known for is high tensile strength (≈ 187MPa). This material was chosen instead of mirrors because of its low cost and high durability. Mirrors are heavy, expensive to purchase and brittle. These problems were solved using a Mylar film that has the same reflective properties, yet much greater tensile strength. The film would be glued to plywood panels, which are hinged to the top surface of the box. A thermal adhesive is to be used. The film would be protected by lamination. There are three of these reflectors mounted by standard chrome-plated hinges. The reflective surfaces are shown in Figure 9 below.

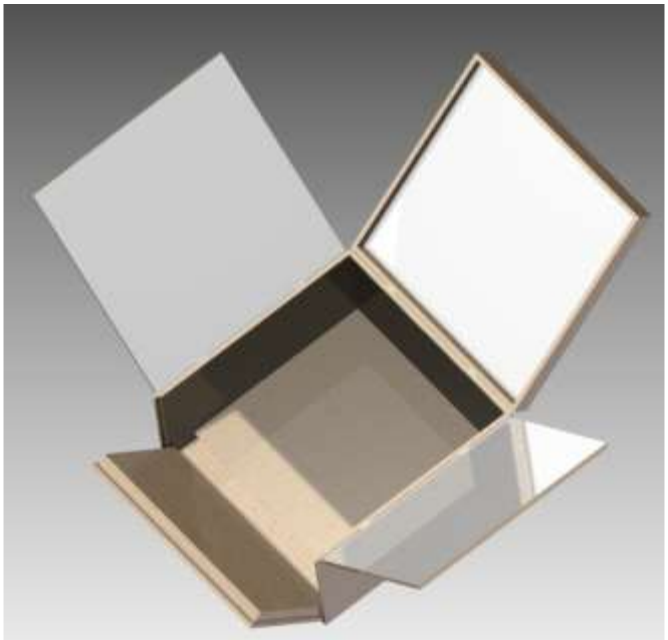

Figure 7: A top view of the solar cooker showing the three reflective surfaces hinged to the top

Reflector Angle Adjustment System

To optimize the amount of sunlight reaching the box during all times of the day, the reflector angles can be adjusted. All three reflectors have this system. The system is comprised of a rigid rod attached to the handle. The other end can be attached to the reflector at different levels to achieve different angles. Figure 10 below shows the holes in the back of the reflectors and the notch in the handle to fit in the rod.

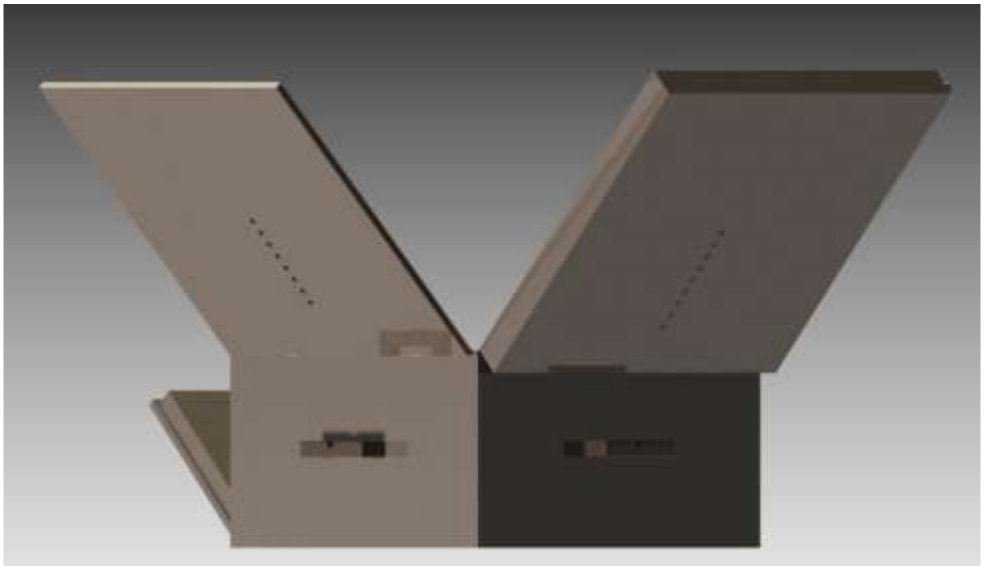

Figure 8: Solar cooker reflector adjustment system

Each hole drilled into the reflector allows for a different angle for the sunrays to hit. The rod locks into the handle with a knob on the end fitting into a slot in the handle. The rods are made from a cast plastic. The adjustment system allows the cooker to remain operable during low sunlight conditions and also when the sun is low in the sky. The system that was implemented was an affordable option that does not involve intricate manufacturing methods.

Cover Plate

The cover plate is an essential element for the complete functionality of the solar cooker. Heat must be trapped effectively within the box to thoroughly cook the food. The main purpose of the cover plate is to allow solar energy to enter the cooker, while trapping the radiation emitted from the surfaces in the box, therefore heating the air inside. Initially it was proposed to implement a double pane glass sheet as the cover plate medium. Although these are proven to be effective in preventing heat loss, glass is heavy, brittle and expensive to manufacture. It was determined that a Plexiglas cover plate would best meet the needs of the cooker through the second weighted evaluation matrix performed. It can be seen in the Economics section of the report that Plexiglas was less expensive to implement into the cooker. It still serves the purpose of allowing solar energy to enter because it is completely transparent, but it is lighter and more durable than glass.

Double pane glass has a pocket of air in between the two panes of glass to provide a thermal resistance layer that further reduces heat loss. In addition to this air gap, the glass is often glazed to trap the long wave radiation in the cooker. If the glass was to be replaced with Plexiglas, than there needed to be a way that radiation was trapped inside the box just as effectively as glass. The solution was to apply a low-emissivity film to the inside surface of the cover plate. This film reduces the amount of long wave radiation escaping through the medium it is applied to (Wang, 2001).

The Plexiglas sheet would be 3/8 ʺ thick and would fit into the box via a groove in the wood at the top of the cooker. To assemble the box, the Plexiglas is inserted into the grooves with the front door open. The groove provides a rigid support system sealing the box from thermal energy losses. The cover plate can be seen in Figure 9 above.

Door Mechanism

A door in the front of the cooker is used to access the pots within the cooker. It is pulled down from the top, with hinges on the base of the door. The configuration resembles that of an over door. The door mechanism can be seen in detail in Figure 11 below.

Figure 9: Front View of solar cooker to illustrate the door mechanism

The door contains all the layers of the adjacent walls; however, it is moveable. The door seals the box from heat loss when closed. The inside of the door when closed sits tight to the other walls, holding it up and ensuring no seams are left open for hot air to flow out.

A failure mode that was identified by the FMEA, as described earlier, was the hinges coming in contact with the ground repeatedly. Contact with the ground could cause dirt and other particles to enter the tolerances and cause seizure of the door. A solution was proposed using the FMEA to lift the cooker off the ground slightly with four wooden feet attached at each corner. These blocks are 2ʺ high and allow the door to open freely without any interference with the ground. The handle of the door can then rest on the ground while food is being retrieved.

Transport

The movement of the box is extremely important for receiving the optimal amount of sunlight in certain conditions and also for protection of the cooker. Many methods were thought up on how to move the cooker; however, cost restraints limited the feasibility of most of the ideas.

It was determined that the cooker was to be transported manually by handles. If this method was to be effective, the cooker needed to be light enough to be lifted by most of the population. It was determined with all the components included the mass of the solar cooker would be 22.7kg. Although this mass estimate is heavier than was expected, two people could carry the cooker, lessening the load they have to carry. The mass was estimated using the densities and volumes of materials and did not include elements such as screws, hinges, and Mylar film.

Along with the handles to transport, the cooker reflectors can fold into the box to make the transport easier. The two side mirrors fold in first, with the back reflector acting as the lid for the box.

The final design with all the parts mentioned above met all the functional requirements and constraints that were outline at the beginning of the term. The final design, in isometric view is shown in Figure 12. A full economic analysis is performed in the following section.

Figure 10: isometric view of final solar cooker

3.5 Engineering Economics

With Mali, Africa as the target area, economics became a large concern. The costs of production, manufacturing, capital and distribution all needed to be low enough to allow the solar cooker to be marketable in a developing country. These costs were considered throughout the design process and provided a fundamental criterion for evaluating preliminary designs.

The first preliminary design, determined by the primary weighted evaluation matrix, had an estimated materials cost of $109.40 (Table 6). This cost estimate was based on retail prices and did not account for mark-up between manufacturers and distributors. A reasonable estimate for the final cost of the solar cooker preliminary design was the retail price divided by two. The estimate of the preliminary design then came to $54.70.

Table 6: Preliminary design retail prices

Item	Description	Quantity	Price
Wood Panels	Siding panels of Standard Spruce Plywood, 1'x2'x3/8''	12	$0.76
Insulation	Fiberglass insulation	4	$1.41
Hinges	Richelieu-Self Closing Hinge-Chrome with mounting screws	7	$0.12
Mirrors	Glass mirrors, 2'X2'	3	$10.00
Mirror Support	Adjustable tilt mirror support system	3	$10.00
Black Paint	Black Board Paint	1	$1.10
Glass Cover	Double Pane, glazed glass panel	1	$10.75
Wheels	360° rotation cart wheels, locking mechanism included	4	$5.00
Screws	Richelieu Quadrex Metal Screws 5/8'' long	20	$0.06
Handles	Wood crafted handles	3	$0.25
		TOTAL	$109.40

The cooker is designed for the population in Mali, Africa therefore the price needed to be much lower than $54.70. The price of the leading competitor in solar cooking is $17.50 for the CooKit (Solar Cookers International, 2010). The retail price of the CooKit is almost $30.00 less than the preliminary design described in Table 6.

After analyzing the preliminary design using the aforementioned design tools, the final product was designed and the cost was estimated, based on retail prices, as $44.88 (Table 7). With the same estimation procedure for the mark-up value of the first design used, the final cost estimate came to $22.44. The estimate does not account for manufacturing costs and labour, and excludes any mark-up needed for profit.

The most significant factor decreasing the price between the preliminary and final design was the exclusion of the wheels and complex mirror support system. The incorporation of handles to transport the box was a simple solution that did not involve ordering wheels from a specific manufacturing company. The handles could be crafted with ease because they are made from a wooden block with a cut-out. The one requirement for the cooker if handles were the method of transport, was that the box needed to be lightweight.

The manufacturing costs of the final design for the solar cooker would be significantly reduced from those of the preliminary design. The preliminary design included a mirror support that must be uniquely manufactured. It is similar to the mechanism that a beach chair uses to adjust the angle of incline. This specialized part would increase the manufacturing prices significantly. The system used in the final design to adjust the angles of the mirrors is a simple system consisting of drilled holes and a rigid wooden rod. Manufacturing costs of the new mirror support system would be small, consisting of installing a hinge on the rod and drilling a series of holes on each mirror panel.

The costs listed in Tables 6 and 7 were retail prices obtained from building supply stores such as Home Depot, Canadian Tire and Totem Building Supplies Ltd. The prices were all retail prices that their respective stores have increased to receive reasonable returns. The prices excluded the mark-ups from the base manufacturing costs and distributors. Also, stores such as Home Depot increase their prices substantially to make a larger profit. Customers purchase their products because of the name of the store and are willing to pay these increased prices. With all this in mind, the cost estimates made were adjusted for mark-up dividing the retail material cost in half, as described above. Capital expenses such as factory space and construction equipment needs to be considered for determination of the final solar cooker price. The final cost estimate would be more accurate if labour prices were included. The final design could be constructed easily and labour could be trained to build the cooker quickly. Manufacturing would involve the installation of hinges, drilling holes and screws, and simple welding tasks for the aluminum core of the box. These jobs require no specialized training other than welding. The simplicity of manufacture will allow the cooker to be reasonably priced and hence increased the accuracy of the cost estimate provided in Table 7.

Table 7: Final Design cost estimate, based on retail prices

Item	Description	Quantity	Price
Wood Panels	Siding panels of Standard Spruce Plywood, 1'x2'x3/8''	12	$0.76
Insulation	Rigid foam insulation 11''x1'11''x3/4''	4	$0.48
Hinges	Richelieu-Self Closing Hinge-Chrome with mounting screws	7	$0.12
Screws	Richelieu Quadrex Metal Screws 5/8'' long	20	$0.06
Reflective Surface	Mylar film, 2mm thick	3	$0.58
Adhesive	Epoxy-resin based, thermally enhanced glue	1	$0.25
Handles	Handles, made out of pine, 6'' length, 3'' high	3	$0.50
Black Paint	Black Board Paint	1	$1.10
Transparent Cover	Plexiglass plate 2'X2'	1	$6.71
Metal Sheeting (inside)	0.04'' Thick, 2'X2' Aluminum sheeting	1	$8.20
Metal Sheeting Inside (Side Walls)	0.04'' Thick, 1'X2' Aluminum Sheeting	3	$4.10
		TOTAL	$44.88
	Accounting for mark-up in the above prices:	**TOTAL**	**$22.44**

3.6 Engineering Science

The performance of the solar cooker relies on how effective the system is in transferring heat to the cooking pot. The two dominant mechanisms of heat transfer that are prevalent in this cooker are conduction and convection. The cooking pot relies on natural convective heat transfer from the air in the box and also conduction between the bottom aluminum panel and the pot. Both conduction and convection are proportional to the temperature difference between the heat transfer surfaces. The effectiveness of the cooker is also judged on how much heat is lost through the walls. The incorporation of insulation into the walls increases the thermal resistance to conduction between the inside surface and outside conditions.

To determine the heat transfer to the pot through convection inside the cooker, the convective heat transfer coefficient needed to be determined. There are several correlations for determining this coefficient; however, the ones used in this particular analysis were for natural convection on vertical and horizontal plates. Several assumptions needed to be used to analyze the convective heat transfer coefficient over the inside cooker surfaces. The main assumption used was that the convective heat transfer from the sides of the cooker was independent of the convection from the bottom aluminum plate. This assumption was used so that the equations of laminar convection over horizontal and vertical flat plates could be used separately. The full calculations for the heat transfer coefficients and heat transfer rates are shown in detail in Appendix C.

To perform a proper analysis of the heat transfer that could occur inside the cooker, several temperature conditions had to be assumed. Since the target temperature of the cooker was set at 70°C, this was assumed to be the inside temperature. The surface temperature of the aluminum was assumed to be 100°C, since the thermal conductivity value of this material is 237 W/mK (Incropera, 2007). To evaluate the fluid properties such as thermal diffusivity and Prandtl Number, the average temperature between the fluid and surface was used. In literature, this is called the film temperature of the boundary layer. Another assumption used in the analysis of convection heat transfer was that the properties of the fluid stayed constant and the fluid could be treated as an ideal gas.

The convective heat transfer coefficient along the vertical walls in the cooker was estimated at 3.976 W/m^2K. Using this value the heat transfer by convection to the pot was estimated at 36.264 W for each wall. The convective heat transfer coefficient of the air between the pot and corrugated aluminum bottom plate was estimated at 6.783 W/m^2K. Although this coefficient was higher than that of the convective coefficient along the vertical walls, the bottom of the pot has less surface area susceptible to convection heat transfer than the side does. The heat transfer rate to the bottom of the pot was determined as 8.486 W. Totaling these heat transfer rates, the overall convection to the cooking pot was found to be 153.54 W at the specified conditions. This is not including the conduction through the pot, however, it is known that the material of cooking pots are very good thermal conductors. The full analysis, including calculations and critical formulas used can be found in Appendix C.

The convection heat transfer rate that was determined confirmed that, in theory, the solar cooker could provide enough heat to cook food. In this analysis, no losses were considered in the cooker. This is not a valid assumption, because the box cannot be perfectly insulated. To judge the effect that losses would have on the overall heat transfer to the food, heat losses through the walls had to be calculated.

The walls of the solar cooker have layers of aluminum, wood, and insulation. The conduction heat transfer through the walls could be calculated using an equivalent thermal resistance circuit. The temperature difference between the inside and outside panels of the box divided by the total thermal resistance to conduction revealed the heat loss due to conduction out of the solar cooker (Incropera, 2007). Heat loss due to convection can be neglected because there is only natural convection occurring inside and outside of the cooker, therefore minimal heat loss compared to conduction.

A full analysis of the heat loss in Appendix C revealed that a total of 78.65 W of heat was lost to the outside of the solar cooker. Knowing that 153.542 W of energy was entering the pot with these conditions, the net heat transfer is *into* the pot. To support the decision of using a rigid foam insulation in between the wood panels, the conduction heat loss was calculated for the cooker, if no insulation was present. This analysis revealed that 351.12 W of heat would be lost from conduction out of the box without insulation. The decision to insert insulation between the layers of wood was justified.

Calculations of the heat losses involved several key assumptions, simplifying the analysis. The heat transfer was assumed to be steady state, and one-dimensional for every wall surface. Another important assumption in the analysis was that the layers of insulation and wood were perfectly connected and no air pockets or contact resistance was present. These assumptions cannot be true in a real situation however can be used to demonstrate the basic effectiveness of the cooker for trapping heat.

4.0 Conclusion

Over the course of the term, the group progressed from initial research to the point where a prototype could be made. Research was conducted in order to develop an understanding of the requirements of a successful solar cooker for the third world. It was determined that the solar cooker would have to be durable, easy to use, portable, cheap and having adequate thermal capacity for cooking. A design was developed through the use of a variety of design tools. First, an idea trigger was used to develop an array of solutions for functional elements. Then, a morphological chart was used in conjunction with a weighted evaluation matrix to develop a preliminary design. This design was determined to be too costly at an estimated $109 to produce. Therefore, the design was reevaluated using reverse engineering techniques and expensive parts were replaced using TRIZ in conjunction with a second weighted evaluation matrix. The new design was compared to existing designs using a quality function deployment, and improvements were identified using a failure modes and evaluation analysis. Finally, a Computer Animated Design (CAD) was created. The new design was estimated to cost $22.44, which was a competitive price for a solar cooker. Moving forward, the group would develop a prototype and test assumptions about heat flow and product durability.

5.0 Project Management

While some work such as research was best done individually, most work was done as a group at weekly meetings. The group met on Thursday nights for at least two hours every week with supplemental meetings on Saturdays and occasionally Mondays. In total, the group met for an average of 6 hours per week.

In order to allow more flexibility in discussions, early meetings were not structured. Discussion in these early 'freeform' meetings covered new research and its relevance to the project as well as original ideas developed by group members.

After three weeks, the group decided that enough research had been compiled and that the critical path had evolved from doing research to formulating a design. For that reason, meetings were structured to reach desired goals. Examples of such goals included developing a morphological chart and conducting a weighted evaluation of different functional elements.

The critical path was different from the Gantt chart (Appendix B) prepared at the beginning of the term in a number of ways. One significant deviation from the Gantt chart was the expected creation of a prototype, which was expected to occur before the interim report. In reality the group is still not ready to build a prototype. Another deviation from the Gantt chart was the relationship between the design process and evaluation. Evaluation was intended to occur after a first design had been chosen, but in reality the two tasks overlapped. The overlap occurred because both design and evaluation took longer than expected. In addition, every evaluation step revealed new problems with the design, causing amendments to the design through the evaluation phase. Finally, the main difference between the Gantt chart and the actual project was the report-writing process. Writing of the interim report began on schedule but lasted longer than expected. As a consequence, editing time was greatly reduced. One area where reality was consistent with the Gantt chart was the research phase, which matched expectation well.

As we neared the end of the term, meetings were held more often to clarify the final aspects of the design and begin delegating for the final presentation and report. For the final presentation, an outline was drawn up and each member was charged with creating a slide and deciding what their section of the presentation would describe.

When writing the final report, specific components of the report were given to group members. These sections were mostly completed on time to start the editing phase. The editing phase took much longer than expected. A system was set up that each group member would edit the final report and send their marked version to the rest of the team. From here, the changes would be discussed and implemented if all of the team agreed upon them. This system of editing allowed everyone to have his or her input into the final compilation of the report.

6.0 Recommendations & Future Developments

Implementation and Intended Use

This design is intended to be more durable and have a higher capacity than its competition. The strategy of durability at the expense of weight suits areas which have a high probability of sunlight and a lack of reliable cooking methods. One such area is sub-Saharan Africa. This group estimates that one third of domestic product in this region is consumed on firewood for cooking. This cooker is intended to be a long-term investment which would serve a family as a reliable source of heat for water purification and cooking.

Prototype Testing

At this point, a design has been created and technical drawings have been created. The next step would be to develop a prototype. The first prototype would be tested in order to check assumptions. First, the design would be weighed to see if estimates of weight were correct. The design would then be tested thermally. This would be done by placing the box in a sunny area with thermocouples embedded in different areas of the box in order to plot the temperature profile in the box during heating. This would allow better estimates of the thermal capability of the box. Finally, the durability of the box would be tested by subjecting the box to static loads, vibration and shock. Once the box failed, the failure modes of the box could be assessed. Target group testing?

Manufacturing

Once a prototype passes testing, a method of manufacturing the box must be developed. Construction of the prototype would be broken down into elementary steps, each of which could be done repeatedly and with low labour cost. Ideally, manufacturing would happen close to the areas of distribution since transportation costs would be reduced. However, it is likely that manufacturing would happen in North America because of better access to materials and better infrastructure.

Distribution

Success of the product would be reliant on good distribution. Since this is a multi-national product, organizations with local knowledge will be necessary. At this point, the best option is to contact an NGO which is already established in the target region. One NGO which already distributes solar cookers internationally is Solar Cookers International, or SCI, and the team has already developed a relationship with their correspondent. This group would probably be contacted for help with distribution.

7.0 Group Statement

To begin, the team realized that there was a wide range of expertise to bring together. The group had experience in technical fields such as social issues in developing countries, heat transfer and CAD modeling as well as numerous professional skills which have been used extensively over the course of the project. Because the group comes from many different backgrounds and has many different strengths, each person's ideas and thoughts sometimes need to be expanded upon and discussed further to provide understanding within the entire group.

Every week the group met twice, primarily working on Thursday nights but with occasional smaller meetings on Saturdays or Mondays. A large portion of each meeting was devoted to planning tasks for the coming week and discussing accomplished tasks from the previous week. Another large part of every meeting was spent discussing and evaluating new ideas, and findings ways to organize and develop our design. Due to the diversity in strengths of different team members, work was distributed based on aptitude rather than equality. Tasks were assigned by each member's expertise. For tasks that were not easily categorized this way, two members would share the task so that there would be a second informed opinion on any decisions. This ensured that everyone's strengths were used, and members who had an interest in the subject matter accomplished that work. Some team members occasionally shouldered a larger burden based on the nature of the workload for a given week.

The overall team dynamic was strong and respectful. Group members were able to discuss their ideas without being shut down. Arguments were resolved respectfully, with talking out different opinions on design ideas and methodology. The team communicated effectively over email and by telephone. Urgent means of communication were always done by phone. Team emails were sent regularly communicating what tasks had been completed and which ones are still in progress. This ensured everyone in the group knew what the other members were doing and deadlines could be met effectively.

Team communication skills grew stronger as the term progressed. Organization of meetings later in the term enabled the team to achieve much great goals than before the interim report. The low mark on the interim report served as a reminder and a harsh reality that more work needed to be done and more communication was essential. After the interim report the team worked more efficiently with each other. The team worked diligently to get a better grasp on our design and utilize the design tools taught in class.

8.0 References

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Appendix A: Design Tools

A.1: Morphological Chart

Design Features	Simple	Intermediate	Complex
Support	• None • Lazy Susan: Cooker rotates on a base plate	• Wheel barrow: handle and 2 wheels on one axle	• Shopping Cart: 4 independent wheels on the bottom for easy 360º movement
Radiation-to-Convection Interface	• Flat black box interior walls • Corrugated walls: wavy interior surface to increase surface area	• Curved basin to eliminate corners: helps to create a convection current to distribute thermal energy	• Fin array: small fins along the entire surface which would greatly increase the amount of convention within the box
Insulation	• Air • Straw • Wood	• Styrofoam • Fibreglass	• Sand: Seeps out more easily, more difficult to contain but has higher heat capacity
Access	• Oven door: attaching a hinge to the front face of the box in order to access the cooking space	• Open top: the top glass plate assembly would lift up to access the cooking space. Moving glass plate could reduce transparency and increase chance of damage to glass	• Slide out entire compartment: have the entire cooking volume able to slide out from the rest of the cooker assembly
Reflector Mounting	• Mirror assembly is attached to the box by hinges. Side mirrors are detachable and can be stored in the oven	• Side mirrors are hinged to main mirror and fold out for use.	• Mylar fabric placed on a metal framework: reduced weight and increased flexibility but some durability and manufacture concerns
Reflector Material	• Plexiglas: more resistant to breaking, and doesn't shatter if	• Polymers e.g. Mylar: Some have very good strength to weight ratios and	• Glass mirrors: easily broken, has higher density, and is most costly

	broken.	are relatively cheap.	option
Base Material	• Wood • Aluminum	• Injection- Moulded Plastic	N/A

Appendix A2: Additional Preliminary Design Drawings

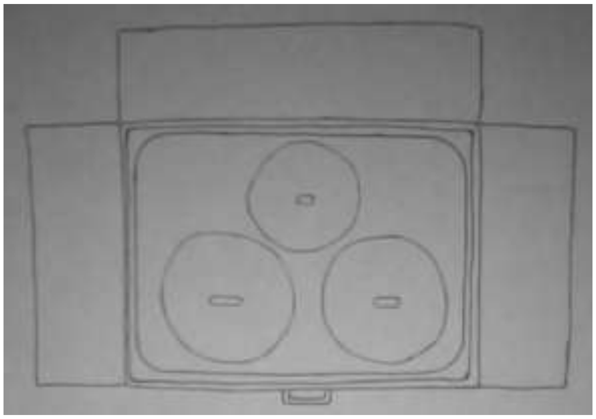


Figure A2.1: Top view of preliminary design

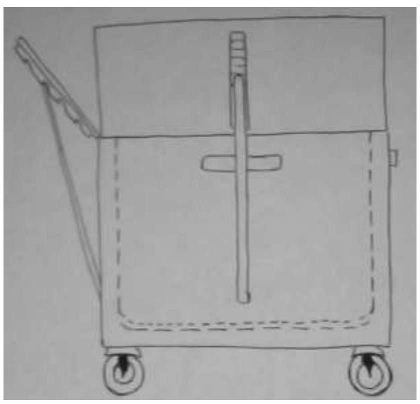


Figure A2.2: Side view of preliminary design showing the mirror adjustment system

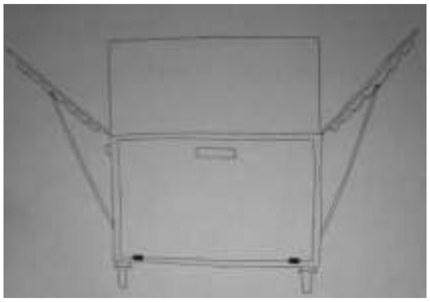


Figure A2.3: Side view showing door

Appendix A3: First Weighted Evaluation Matrix

		Transport				Inside surface			Insulation		Access to Food		Mirror Arrangement		Cover Plate (Transparent Medium)		
	Weights	Box on Ground	Handles	Wheel-barrow	Four wheels (360° freedom)	Flat walls, 90° corners	Rounded inside, no 90° corners	Fin array or corrugated inside walls	Straw	Styrofoam/ Fiberglass	Glass slides/ pulled open	Oven door	3 mirrors hinged to top	Pivoting mirrors with sun dial	Single Pane Glass	Double Pane glass with low-e coating	Plexi-glass
Thermal Capabiltiy	30	4	4	4	4	1.5	3	4	2.5	3.5	3	3.5	3	4	3	4	2.5
Safety	25	1	2	3	4	4	4	3.5	4	4	3	4	4	3.5	3	3	4
Cost	20	4	4	3.5	3	4	2.5	2	4	3	3.5	2.5	4	2	3.5	3	4
Durability	10	3	4	3	3	4	4	3	3	4	3.5	3	3.5	2	3	3	3.5
Ease of Use	10	1	2	3	4	4	4	3.5	4	4	3	4	3.5	3	4	4	4
Assembly	5	4	4	3.5	2.5	4	3	2	3	3	3.5	2.5	4	3	3.5	3	4
TOTAL	100	**285**	**330**	**342.5**	**362.5**	**325**	**335**	**322.5**	**340**	**360**	**317.5**	**338**	**360**	**312.5**	**323**	**340**	**350**

Appendix A4: Second Weighted Evaluation Matrix

		Transport				Inside surface			Insulation	
	Weights	Box on Ground	Handles	Wheelbarrow	Four wheels(360° freedom)	Flat walls, 90° corners	Rounded inside, no 90° corners	Fin array or corrugated inside walls	Straw	Styrofoam/ Fiberglass
Safety	15	1	2	3	4	4	4	3.5	4	4
Cost	40	4	4	3.5	3	4	2.5	2	4	3
Durability	10	3	4	3	3	4	4	3	2	4
Ease of Use	10	1	2	3	4	4	4	3.5	4	4
Assembly	5	4	4	3.5	2.5	4	3	2	3	3
Thermal Capabiltiy	20	4	4	4	4	1.5	3	4	2.5	3.5
TOTAL	100	**315**	**350**	**342.5**	**342.5**	**350**	**315**	**287.5**	**345**	**345**

Access to Food		Mirror Arrangement		Cover Plate (Transparent Medium)		
Glass slides/ pulled open	Oven door	3 mirrors hinged to top	Pivoting mirrors with sun dial	Single Pane Glass	Double Pane glass with low-e coating	Plexi-glass
3	4	4	3.5	3	3	4
3.5	2.5	4	2	3.5	3	4
3	4	3.5	2	3	3	3.5
3	3.5	3.5	3	4	4	4
3.5	2.5	4	3	3.5	3	4
3	3.5	3	4	3	4	2.5
322.5	**317.5**	**370**	**277.5**	**332.5**	**330**	**365**

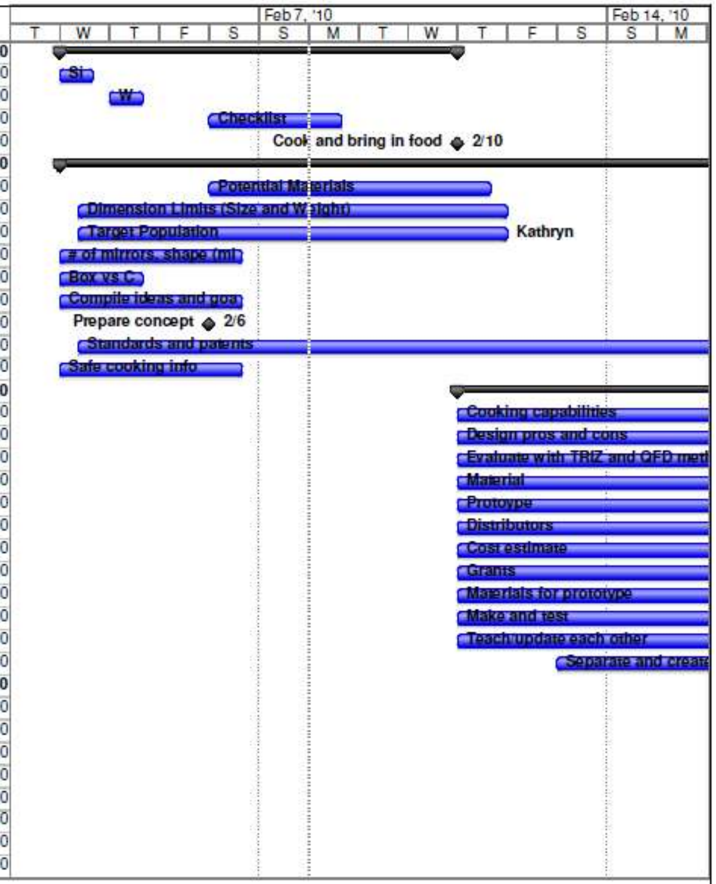
Appendix A5: QFD

LEGEND	
Strong Correlation	O
Some Correlation	∩
No Correlation	⊘

CUSTOMER REQUIREMENTS	WEIGHTING	ENGINEERING SPECIFICATIONS: Mirror Size	Cooker Volume	Cooker Weight	Manufacturig Cost	Access to food	Material Strength	Cooking Time	Assembly Cost	Cooker Temperature	BENCHMARKS: Parabolic Mirror	CooKit	Our Design
Inexpensive	35%	O	O	O	O	⊘	O	∩	O	∩	1.0	4.0	2.5
Thermal Capabilities	18%	O	O	∩	⊘	∩	O	O	⊘	O	3.0	3.0	3.0
Durable	15%	⊘	∩	∩	⊘	∩	O	⊘	⊘	∩	3.0	1.0	3.5
Cooking Volume	12%	⊘	O	O	⊘	⊘	O	O	∩	⊘	2.0	2.0	4.0
Cooker Weight - light weight	10%	O	O	O	⊘	∩	O	⊘	∩	∩	2.0	4.0	2.0
Easy to use	10%	∩	∩	∩	⊘	O	∩	O	⊘	O	2.5	4.0	3.0
	100%										**203.0**	**313.0**	**292.0**

Appendix B: Gantt Chart

ID	Task Name	Start	Finish
1	**Bring Food**	**Wed 2/3/10**	**Wed 2/10/10**
2	Sign up	Wed 2/3/10	Wed 2/3/10
3	Who is bringing what	Thu 2/4/10	Thu 2/4/10
4	Checklist	Sat 2/6/10	Mon 2/8/10
5	Cook and bring in food	Wed 2/10/10	Wed 2/10/10
6	**Research and Conception**	**Wed 2/3/10**	**Thu 2/18/10**
7	Potential Materials	Sat 2/6/10	Thu 2/11/10
8	Dimension Limits (Size and Weight)	Wed 2/3/10	Thu 2/11/10
9	Target Population	Wed 2/3/10	Thu 2/11/10
10	# of mirrors, shape (mirrors general)	Wed 2/3/10	Sat 2/6/10
11	Box vs Concentration	Wed 2/3/10	Thu 2/4/10
12	Compile ideas and goals	Wed 2/3/10	Sat 2/6/10
13	Prepare concept	Sat 2/6/10	Sat 2/6/10
14	Standards and patents	Wed 2/3/10	Thu 2/18/10
15	Safe cooking info	Wed 2/3/10	Sat 2/6/10
16	**Prelim Designs**	**Thu 2/11/10**	**Sun 2/28/10**
17	Cooking capabilities	Thu 2/11/10	Thu 2/18/10
18	Design pros and cons	Thu 2/11/10	Thu 2/18/10
19	Evaluate with TRIZ and QFD methods	Thu 2/11/10	Sun 2/28/10
20	Material	Thu 2/11/10	Sun 2/28/10
21	Protoype	Thu 2/11/10	Thu 2/18/10
22	Distributors	Thu 2/11/10	Thu 2/18/10
23	Cost estimate	Thu 2/11/10	Thu 2/18/10
24	Grants	Thu 2/11/10	Thu 2/18/10
25	Materials for prototype	Thu 2/11/10	Thu 2/18/10
26	Make and test	Thu 2/11/10	Thu 2/18/10
27	Teach/update each other	Thu 2/11/10	Sun 2/28/10
28	Separate and create multiple ideas for differe	Sat 2/13/10	Thu 2/18/10
29	**Evaluation**	**Thu 3/11/10**	**Sat 3/13/10**
30	Final ideas	Thu 3/11/10	Sat 3/13/10
31	Pros and cons	Thu 3/11/10	Sat 3/13/10
32	Weightings	Thu 3/11/10	Sat 3/13/10
33	Marking scheme	Thu 3/11/10	Sat 3/13/10
34	Cost	Thu 3/11/10	Sat 3/13/10
35	Re-evaluation Meeting	Sat 3/13/10	Sat 3/13/10
36	Product Decision	Sat 3/13/10	Sat 3/13/10
37	READING WEEK	Fri 2/19/10	Sun 2/28/10



Project: 19_NewGanttChart
Date: Mon 2/8/10

Task		Rolled Up Task		External Tasks	
Progress		Rolled Up Milestone	◇	Project Summary	
Milestone	◆	Rolled Up Progress		Group By Summary	
Summary		Split		Deadline	⇩

Page 1

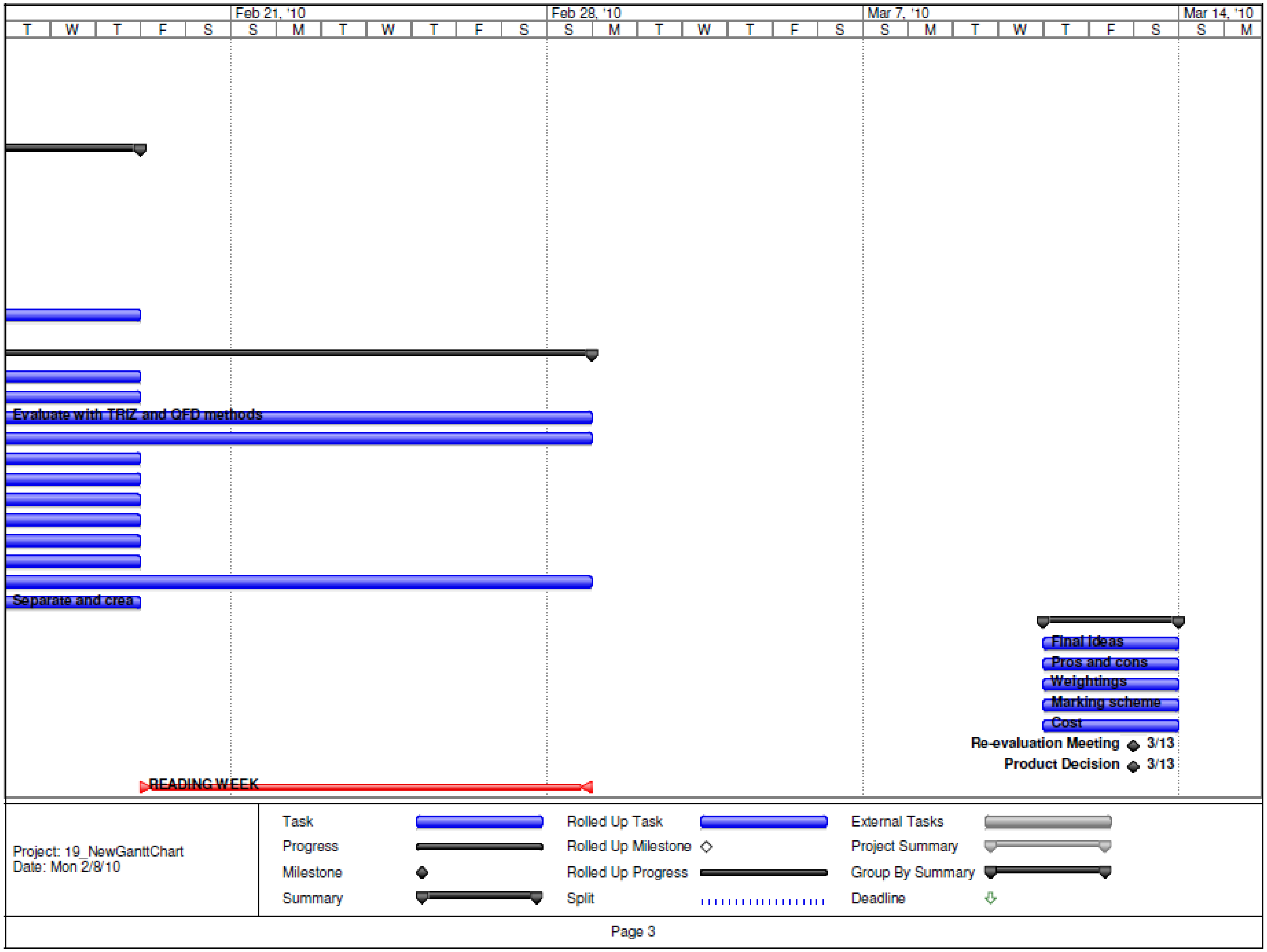
ID	Task Name	Start	Finish
38	**Interim Report + Pres. Delegation**	**Thu 2/18/10**	**Fri 3/5/10**
39	Delegate	Thu 2/18/10	Thu 2/18/10
40	Write	Thu 2/18/10	Sat 2/27/10
41	Combine	Sat 2/27/10	Sun 2/28/10
42	Edit	Sun 2/28/10	Wed 3/3/10
43	Practice presentation	Sun 2/28/10	Wed 3/3/10
44	Interim Presentation	Wed 3/3/10	Wed 3/3/10
45	Interim Report	Fri 3/5/10	Fri 3/5/10
46	**Final Report + Pres. Delegation**	**Sat 3/13/10**	**Fri 4/9/10**
47	Final Ideas	Sat 3/13/10	Sat 3/13/10
48	Delegate	Sat 3/13/10	Sat 3/13/10
49	Progress Meeting	Thu 3/18/10	Thu 3/18/10
50	Write	Sat 3/13/10	Thu 3/25/10
51	Combine	Thu 3/25/10	Sun 3/28/10
52	Edit	Sun 3/28/10	Wed 3/31/10
53	Practice presentation	Sun 3/28/10	Wed 3/31/10
54	Final Presentation	Wed 3/31/10	Wed 3/31/10
55	Final Report	Fri 4/9/10	Fri 4/9/10

Feb 7, '10 — Feb 14, '10

T W T F S S M T W T F S S M

Project: 19_NewGanttChart
Date: Mon 2/8/10

Task, Progress, Milestone, Summary, Rolled Up Task, Rolled Up Milestone, Rolled Up Progress, Split, External Tasks, Project Summary, Group By Summary, Deadline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Product Decision 3/13
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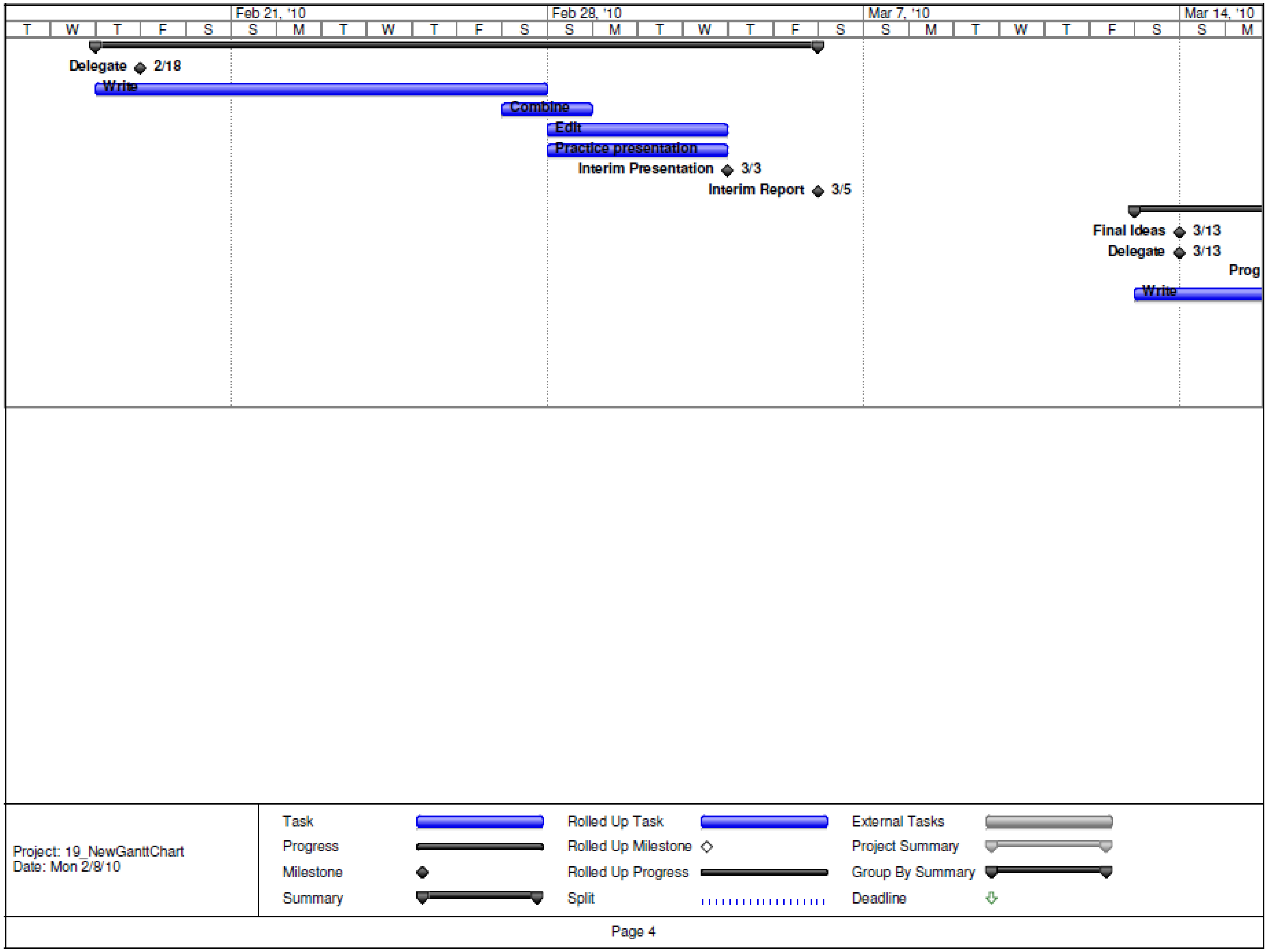
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Interim Report 3/5
Final Ideas 3/13
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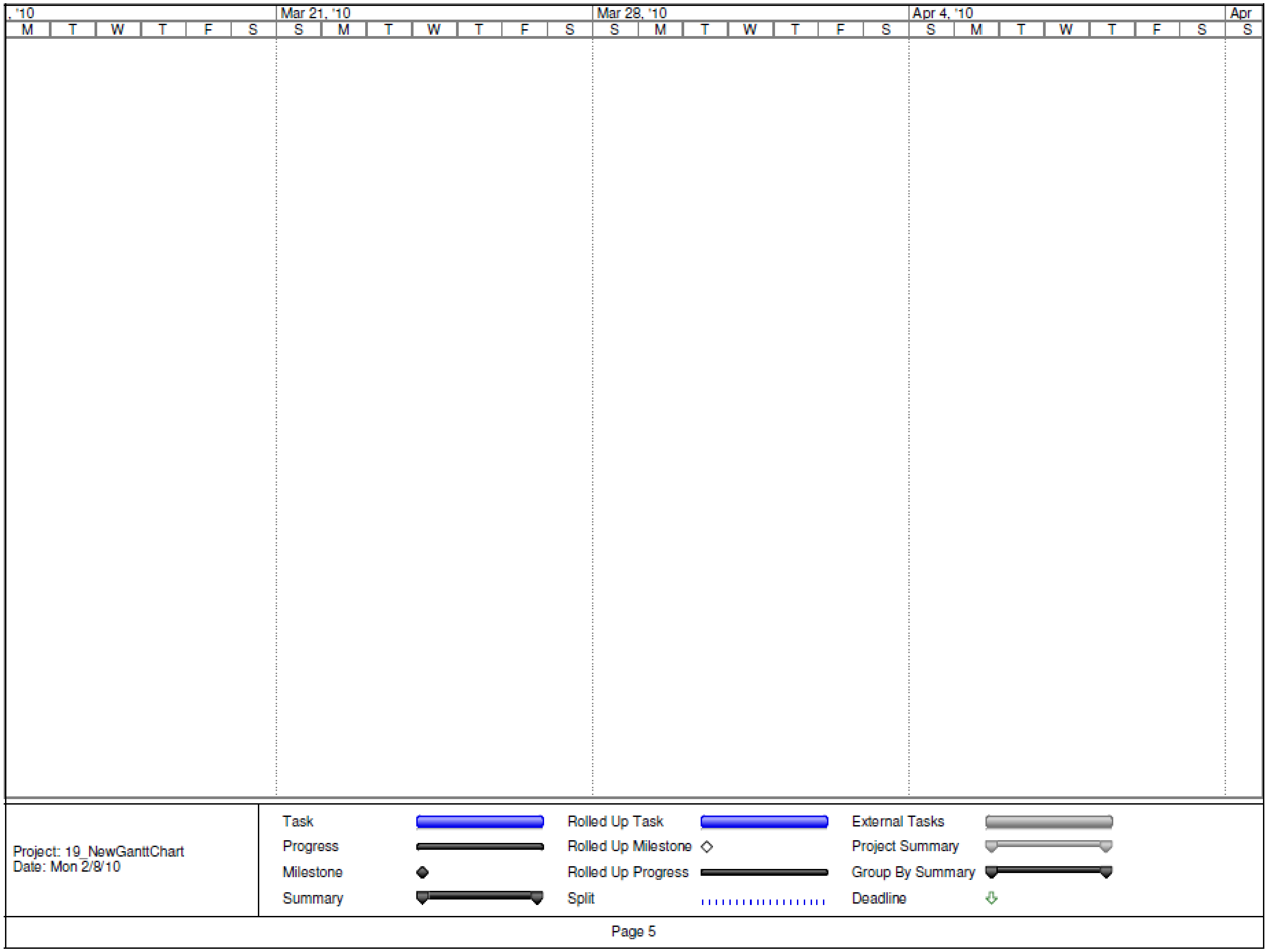
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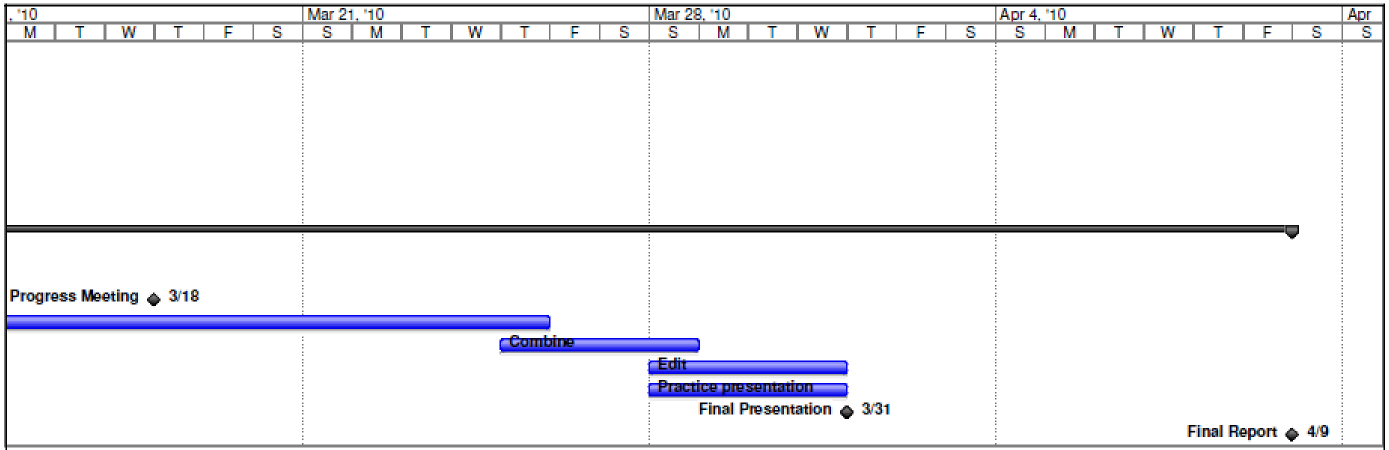

Project: 19_NewGanttChart
Date: Mon 2/8/10

Task		Rolled Up Task		External Tasks	
Progress		Rolled Up Milestone		Project Summary	
Milestone		Rolled Up Progress		Group By Summary	
Summary		Split		Deadline	

Appendix C: Manual Calculations

Convective Heat Transfer to the Cooking Pot (Incropera, 2007)

First, the average heat transfer coefficients need to be calculated for the vertical and horizontal walls of the cooker.

The Nusselt Number equation used for laminar flow over a vertical wall is:

$$Nu_L = \frac{\mathrm{h}L}{k} = 0.68 + \frac{0.670 \times Ra_L^{1/4}}{[1 + (0.492/Pr)^{9/16}]^{4/9}}$$

Where: Nu_L is the average Nusselt Number over the plate

h is the average convective heat transfer coefficient over the plate

L is the characteristic length of the plate

K is the thermal conductivity of the fluid

Ra_L is the Rayleigh number

Pr is the Prandtl number

The Nusselt Number equation used for laminar flow over a horizontal wall is:

$$Nu_L = \frac{\mathrm{h}L}{k} = 0.15 \times Ra_L^{1/3}$$

This equation is valid for:

$$10^7 \leq Ra_L \leq 10^{11}$$

To calculate the Rayleigh number:

$$\frac{Ra_L = g\beta(T_s - T_\infty)L^3}{\upsilon\alpha}$$

Where: β is the expansion coefficient

T_s is the surface temperature

T_∞ is the temperature of the fluid

g is the gravitational constant

α is the thermal diffusivity

ν is the kinematic viscosity of the fluid

Assumptions had to be made to analyze the cooker without testing. Some of these assumptions include:

T_∞ = 70^{o}C (Inside fluid temperature, originally unaffected by hot inside surfaces)

T_s = 100^{o}C (Aluminum temperature)

$T_f = (T_\infty + T_s)/2$ (Film temperature, temperature that fluid properties are evaluated at)

Fluid Properties:

$\nu = 22.018 \times 10^{-6}\ m^2/s$

$\alpha = 31.58\ \times 10^{-6}\ m^2/s$

$L_{vertical} = 0.3048\ m$

$L_{Horizontal} = 0.6096\ m$

$\mathrm{Pr} = 0.695$

$\beta = 2.79 \times 10^{-3}$

$k = 30.76 \times 10^{-3}\ W/mK$

Rayleigh Numbers:

For horizontal Plate (Bottom surface of cooker): Ra_L= 719862302 = $7.2\ \times 10^{8}$

For vertical plate (Side walls of cooker): Ra_L = 3.3×10^{7}

Using the above information the convective heat transfer coefficients can be found for the heat transfer from the side and bottom panels in the solar cooker.

Convective Heat Transfer Coefficient for Vertical Walls:

$\mathrm{h} = 3.976\ W/m^2K$

Convective Heat Transfer from Vertical Walls:

$q_{convection,vertical} = A_S \mathrm{h}(T_S - T_\infty)$

Where q is the convection heat transfer from the vertical walls in the solar cooker

A_s is the surface area of the pot that is exposed to the heat transfer from the vertical walls

T_s is the surface temperature of the pot (Assumed to initially be at room temperature of 20^{o}C)

T_∞ is the temperature of the fluid in the cooker

Assuming standard pot dimensions of:

Diameter= D =10 in = 0.254m

Area of Pot Side: 0.1824 m^2

$q_{convection,vertical}$ = 36.264 W

Convective Heat Transfer Coefficient for Bottom Wall:

$\mathrm{h} = 6.783\ W/m^2K$

Convective Heat Transfer From Bottom Wall:

$q_{convection,\mathrm{horizontal}} = A_S \mathrm{h}(T_S - T_\infty)$

Where q = convection heat transfer from the bottom wall of the solar cooker

A_S is the surface area of the bottom of the pot

T_S is the bottom surface temperature of the pot (Assumed to initially be at room temperature of 20°C)

Assuming the same dimensions of the pot:

Area of pot bottom: 0.04104 m^2

$q_{convection,\mathrm{horizontal}} = 8.486\ W/m^2K$

The total convective heat transfer to the pot is the sum of all four vertical walls and the bottom plate heat transfer rates.

$q_{total} = 153.542\ W$

Heat Losses Through the Walls

Using the thermal conductivities of the materials in the walls, the heat losses through the walls can be calculated.

Assumptions:

- Steady state heat transfer
- 1-Dimenional heat transfer through each wall
- No internal generation
- No contact resistance between layers in walls

- Natural convection inside the box does not contribute to heat loss

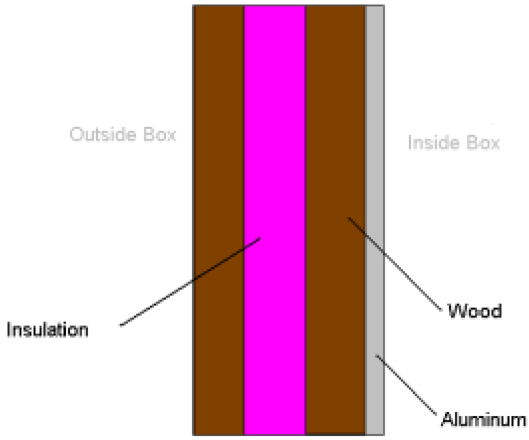

Figure B.1: Cross Section of cooker wall where heat can be lost

Heat transfer is occurring from the inside to the outside of the box through conduction. Natural convection inside the box can be considered negligible compared to the conduction heat transfer through the wall materials. The heat transfer system can be represented as an equivalent thermal circuit. The thermal circuit has four separate resistances in series:

$$R_{Total} = R_{Aluminum} + R_{wood,1} + R_{insulation} + R_{wood.2}$$

The separate conduction resistances are characterized by the thermal conductivities of the material, thickness of material and cross sectional area.

$$R_{conduction} = \frac{L}{kA}$$

Where L is the thickness of the material

K is the thermal conductivity of the material

A is the cross sectional area of the material

The thickness values for the materials are:

L_{wood} = 0.0127m

$L_{insulation}$= 0.01905m

$L_{aluminum}$ = 0.001016m

The thermal conductivities of the materials are:

k_{wood}= 0.12 W/mK

$k_{aluminum}$ =237 W/mK

$k_{insulation}$ = 0.026 W/mK

Using the above values, the total resistance through the side walls was calculated as:

R_{Total} = 5.083 K/W

To calculate the heat transfer through the side walls, the following equation must be used:

$$q = \frac{T_i - T_o}{R_{total}}$$

Where: Ti is the internal surface temperature of the box

To is the outer surface temperature of the box

Assuming the outside of the box is at the external temperature, we can calculate the heat loss of the box. If it 20 degrees Celsius outside and the inside aluminum temperature is 100 degrees Celsius, the heat transfer due to conduction out of the vertical walls is:

q = 15.73 W

The five surfaces by which heat losses could occur through the same thermal circuit gives a total heat loss of:

$$q_{loss,insulation} = 78.65\ W$$

Without the insulation in the box, the heat transfer loss would be 70.2 W per wall, therefore a total heat loss of:

$$q_{loss,no\ insulation} = 351.12\ W$$