Solar Oven Final Report

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Abstract

Solar energy is a popular renewable resource hoping to gain more widespread use in the near future. Solar energy can be harnessed in many ways beyond the solar panels we typically think of when thinking of solar energy. Another way is to harness the energy of the sun to be used for heat, rather than electricity, with a solar oven. With the Solar Oven Design Project, teams were tasked with modeling, building, testing, and analyzing a solar oven. First by modeling the oven in Excel to optimize all dimensions and aspects of the oven, while keeping in mind the overall cost of the oven. The oven was then built and tested. The process was repeated with a second and final oven after reviewing any flaws and rectifying them. Our final oven was made up of an oven chamber (14cm x 14cm x 5cm), an outer box (26cm x 26cm x 11cm), octagonal reflectors, wadded cardboard for insulation, and two sheets of Mylar for the window. With these conditions, our oven was predicted to reach ***185*** degrees Celsius on our test day, with a maximum actual temperature reached of ***182*** degrees Celsius.

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1 Introduction

The goal of the Solar Oven Design Project was to gain teamwork skills as well as design experience through the planning, construction, and testing of a cost-efficient solar oven. Teams had to divide up tasks evenly while still playing to all the members' strengths. Clear and effective communication throughout the entire design process was one of the most important tools to keep a strong, effective group dynamic. By following the entire design process from beginning to end, the team got great experience with this process. We learned first how to use an Excel model to properly reflect an actual product, and how to manipulate certain values within a design equation to maximize the efficiency of our oven while minimizing cost. After building the first oven, we were able to figure out a better and more efficient process for building that not only took less time, but ensured the oven was built with more accuracy by dividing up tasks among group members. By ensuring a relatively simple oven was built, with a cheap cost, the oven can be used in underdeveloped countries to cook food and sterilize drinking water. The most difficult part was ensuring our oven was as cheap as possible, while still completing the required task, and completing it well. We also had to ensure our design of the oven was simple enough that we would be able to build it accurately. Our oven design and materials could be sent to underdeveloped countries, with clear instructions, and they would be able to have their own, fully functioning oven for very cheap, increasing their quality of life drastically.

2 Design Theory and Analytical Model

The solar oven design project revolves around accurately predicting the equilibrium temperature reached by our solar oven through the use of equations and an analytical model. The design theory of the project is fairly important as the design specifications directly impact the overall predicted temperature as well as the efficiency of the solar oven. In order to successfully model the solar oven, it is essential to understand the interactions between a solar oven and its environment (the sun) to harness the energy. Placing the oven in direct sunlight results in an increase in the temperature of the oven chamber, and the temperature eventually reaches an equilibrium in which the energy entering the oven chamber is equivalent to the energy leaving the chamber. In order to achieve our initial goal of accurately predicting the equilibrium temperature, we must first seek an equation that relates power absorbed ($P_{Absorbed}$) and power left (P_{Out}) to the specific design requirements of the solar oven. Equilibrium Temperature is defined by the following equation:

$$P_{Absorbed} = P_{Out}$$

The power absorbed by the system and leaving the system, which in this case is the solar oven, is affected by the three modes of heat transfer. Radiation is the type of heat transfer most responsible for the increase of temperature inside the oven chamber, since the electromagnetic waves travel from the sun causing the increased movement of particles that results in a temperature increase. The other modes of heat transfer, conduction and convection, are responsible for the equilibrium in the system, since heat must leave the system for $P_{Absorbed} = P_{Out}$. Conduction causes heat loss through the side and bottom of the oven, while convection causes the heat loss through the window and areas of insulation that are not tightly packed.

In order to calculate the power absorbed by the oven, we must multiply the area of the oven window perpendicular to the sun's rays m^2 by the solar power density I_o (W/m^2).

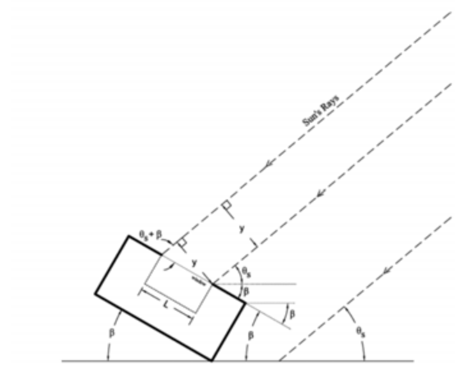


Figure 1: Solar Oven Geometry

While the area of the window is calculated as $A_w = length * width$, the area needed is the area perpendicular to the sun's rays, which is calculated by $y * width$. The value of y is determined through the equation $y = L * sin(\theta_s + \beta)$, where θ_s is the angle the rays create with the ground and $\beta = \beta$ is the angle the window makes with the ground. The oven performs the most optimally when $\theta_s + \beta$ is equal to 90 degrees. Through the multiplication of the perpendicular area and the solar power density we are left with the equation:

$$P_{incident} = I_o W L sin(\theta_s + \beta) \text{ or } I_o A_w sin(\theta_s + \beta)$$

$$\begin{aligned}
I_o &= \text{ solar power density } (W/m^2) \\
W &= \text{ width of window } (m) \\
L &= \text{ length of window } (m) \\
A_w &= \text{ area of window } (m^2) \\
\theta_s &= \text{ angle sun rays make with the ground } (^\circ) \\
\beta &= \text{ angle window makes with the ground } (^\circ)
\end{aligned}$$

In order to more accurately represent the power entering the oven chamber, we calculate the power transmitted through the window. The equation for this is:

$$P_{transmitted} = P_{incident} * \tau^n$$

$\tau =$ the optical transmission constant (between 0 and 1)
$n =$ number of window layers

For our ovens, we utilized two layers of mylar sheets as our window, meaning τ was .92 and the n was 2. The use of a double layered window has benefits and drawbacks, namely less energy is radiating into the oven chamber, but the energy is escaping less quickly through convection compared to a single layered window. Comparing a single layered window and a double layered window, our group concluded the double layered window resulted in a large predicted temperature due to the negation of some heat loss. After accounting for the window parameters, our group needed to consider the power absorbed by the walls of the oven chamber, which is represented by the equation:

$$P_{absorbed} = a * P_{transmitted}$$

$a =$ absorption factor of chamber walls (between 0 and 1)
$P_{absorbed} =$ power absorbed by the oven walls

By combining all of the previous equations we are left with the final equation for absorbed power:

$$P_{absorbed} = I_o A_w \tau^n a sin(\theta_s + \beta)$$

The absorption factor should ideally be close to a value of 1 and this is achieved by making the color of the inside chamber black, which results in an absorption factor of 0.9. By looking at the equation for power absorbed it's evident that we want to maximize area of the window, the transmittivity constant of our window material, as well as the absorption factor of the chamber walls in order to maximize $P_{absorbed}$. The addition of reflectors to the solar oven introduces a new variable known as gain (G) into the equation that results in additional energy entering the oven chamber. Incorporating reflectors on our solar oven effectively increases the area of the window that is perpendicular to the sun's rays, also known as the variable y. Utilizing octagonal reflectors on the solar oven, the equation for $P_{incident}$ can be written as:

$$P_{window} = I_o[WL + 4rWMsin(\alpha) + 4r\frac{(Msin(\alpha))^2}{2}]$$

$$P_{window} = I_o WL[1 + 4r\frac{M}{L}sin(\alpha) + 4r\frac{(Msin(\alpha))^2}{2WL}]$$

$$P_{window} = I_o A_w[1 + 4r\frac{M}{L}sin(\alpha) + 4r[\frac{M}{L}]sin(\alpha)]^2\frac{L}{2W}$$

In the case that the oven window is a square, the equation can be further rewritten as:

$$P_{window} = I_o A_w[1 + 4r\frac{M}{L}sin(\alpha)(1 + \frac{1}{2}\frac{M}{L}sin(\alpha))]$$

The gain equation for octagonal reflectors can be derived and written as:

$$G_{octagonal} = 1 + 4r\frac{M}{L}sin(\alpha)(1 + \frac{1}{2}\frac{M}{L}sin(\alpha))$$

$M =$ length of the reflector
$\alpha =$ angle between the sun's rays and the reflectors ($^\circ$)
$r =$ reflectivity coefficient of the reflectors (.7 for almost smooth foil)

The variable α can be solved for by using the equation:

$$sin(\alpha) = \frac{-\frac{M}{L} \pm \sqrt{(\frac{M}{L})^2 + 8}}{4}$$

After calculating the α value, Ω (the angle at which the reflectors are attached to the oven) can be calculated by adding α to 90 degrees $(\theta_s + \beta)$. Our group used a 3 $\frac{M}{L}$ design for both of our solar ovens, meaning our α was 16.31° and Ω was 106.31°. By combining the gain equation we derived earlier with the equation for power absorbed without reflector we are left with:

$$P_{new} = GP_{old}$$

While the power being absorbed by the oven is important, we must also account for the heat loss through convection, conduction, and radiation to calculate P_{out} (the power leaving the system) to accurately predict the equilibrium temperature of the oven. The equation for P_{out} can be represented by:

$$P_{out} = (U_{sb}A_{sb} + U_wA_w)(T_{io} - T_{ambient})$$

$U_{sb} =$ heat transfer coefficient walls of oven chamber ($W/m^2 *^\circ C$)
$A_{sb} =$ area of sides and bottom of oven chamber (m^2)
$U_w =$ heat transfer coefficient of the window ($W/m^2 *^\circ C$)
$A_w =$ area of the window (m^2)
$T_{io} =$ temperature in the interior chamber of the oven ($^\circ C$)
$T_{ambient} =$ temperature of the air surrounding the oven ($^\circ C$)

The heat transfer coefficient for sides and bottom of the interior oven chamber is dependent on the thickness of the cardboard, insulating material, and thickness of the insulation. U_{sb} can be calculated with the following equation:

$$U_{sb} = \frac{1}{\frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3}}$$

The insulation used for both of our ovens was wadded newspaper, which has a thermal conductivity value of .123 $W/(m^2 *^\circ C)$. For both ovens our group used .06 meters of insulation in order to provide adequate insulation, but also preventing a large increase in the weight of the oven. The newspaper is also more cost efficient compared to other possible insulators such as Styrofoam.

The other heat transfer coefficient pertinent to the solar oven is U_w, which is the heat transfer coefficient for the window.

The heat transfer coefficient for the window is dependant on the number of layers utilized as well as the internal temperature of the solar oven. Increasing the layers of the window causes the oven to be more efficient, and as the temperature of the oven increases the efficiency decreases due to an increased value of U_w. U_{sb} and U_w essentially represent the conductivity of heat of the solar oven, which is essential in determining the power leaving the solar oven.

By setting P_{out} equal to $P_{absorbed}$ we are left with the equation:

$$T_{io} = T_{ambient} + \frac{I_o A_w \tau^n a sin(\theta_s + \beta)}{(U_{sb} A_{sb} + U_w A_{w)}}$$

Through this equation we can calculate T_{io} using our mathematical model in Excel.

Solar Oven Comparisons				
Param.	**Oven 1**	**Oven 2**	**Units**	**Description:**
Fixed Input Parameters				
τ	0.92	0.92		transmissivity for a single layer of Mylar
a	0.9	0.9		absorption factor of oven chamber and contents
r	0.7	0.7		
$V_{chamber}$	0.001	0.001	m^3	volume of the oven chamber
Variable Input Parameters				
$T_{ambient}$	21	21	°C	ambient temperature
I_o	1000	1000	W/m^2	solar power density
θ_s	44	44	°	angle of the sun's rays with respect to the ground
β	46	46	°	angle of the top surface of the oven with respect to the ground
Design Input Parameters				
L	0.12	0.14	m	length of oven window
W	0.12	0.14	m	width of oven window
n	2	2		# of layers of mylar
M/L	3	3		ratio of reflector length to window length
Calculated Input Parameters				
A_w	0.0144	0.0196	m^2	area of the window
A_{sb}	0.047733	0.048171429	m^2	area of the sides and bottom of the cooking chamber
h	0.069444	0.051020408	m	height of oven chamber (>5)
U_{sb}	1.881453	1.440702782	$W/(m^2 \cdot °C)$	heat transfer coefficient for the sides and bottom of the cooking chambe
M	0.36	0.42	m	length of the reflectors
α	16.30655	16.30654852	°	angle of sunlight with respect to the reflectors
Ω	106.3065	106.3065485	°	lid angle
G	4.351848	4.351847733		gain from adding octagonal reflectors
Variables for Heat Transfer Coefficient Calculation				
x1	0.004	0.004	m	inner cardboard wall thickness
x2	0.05	0.07	m	insulation thickness
x3	0.004	0.004	m	outer cardboard wall thickness
k1	0.064	0.064	W/(m*°C)	inner cardboard wall thermal conductivity
k2	0.123	0.123	W/(m*°C)	insulation thermal conductivity
k3	0.064	0.064	W/(m*°C)	outer cardboard wall thermal conductivity
Cost-Based Performance Index				
Weight	1.256350	1.690037	lbs	approx. weight - likely an underestimation
Foil	0.257991549	0.351155164	m^2	amount of foil used
# paper	1	2		pieces of black paper used
cardboard	0.454803	0.611441	m^2	amount of cardboard used
labor	5	5	$	fixed cost of labor
PI_{cost}	24.00963	23.08284		approx. cost based performance index
Predicted Output				
T_{io}	176.32	186.3	°C	predicted internal oven temperature

Figure 2: Excel prediction model for both ovens.

Since U_w is directly related to the increase of internal temperature, we must plot the line U_w double versus the predicted T_{io}, and the intersection of these two lines is the true equilibrium temperature (T_{io}) of our solar oven.

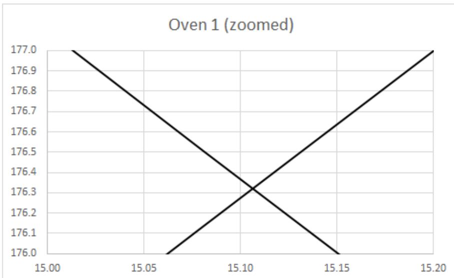


Figure 3: First oven predicted T_{io}

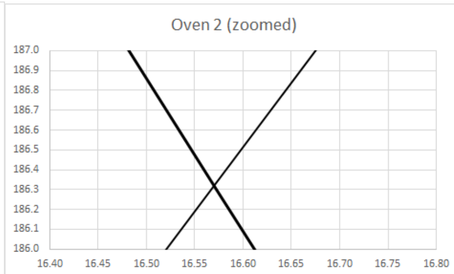


Figure 4: Second oven predicted T_{io}

3 Design Requirements

3.1 Oven Design Constraints

- The cooking chamber must have a volume of 1,000cm^3
- Cooking chamber and window dimensions must be at least 5cm each.
- The window of the oven must be a square ($width = length$).
- The cooking chamber must have a rack to place the biscuit on to keep it off of the walls of the cooking chamber.
- There must be convenient access to the cooking chamber.
- The oven must have a way to get a thermometer from the side of the oven into the cooking chamber, not through the window.
- The plastic casing of the thermometer cannot be inside the oven or within the reflector field.
- The M/L ratio must be less than or equal to 3 (length of the reflectors/length of the window).
- The oven must reach a minimum temperature of 100 degrees Celsius.
- Parabolic reflectors are not allowed.
- Focusing lenses are not allowed.
- The oven must be freestanding.
- The cost of any additional supplies cannot surpass $20.00.

3.2 Practical Constraints

- Cover the inside of the oven chamber with black paper to better absorb heat.
- The cooking chamber should be wider than it is deep, because a larger window allows for more sunlight to enter the cooking chamber.
- Angle the reflectors properly so that the maximum amount of sunlight will enter into the cooking chamber.
- Use octagonal reflectors rather than trapezoidal to increase accuracy of the predicted temperature.
- Use two Mylar sheets for the window with a 1-2cm gap between them.
- Attach all pieces together with heat resistant tape to prevent melting and/or any heat loss through the tape.
- Pack as much wadded newspaper as possible into the outside box to create better insulation.

4 Design Description

4.1 Oven 1: The Prototype

After looking at the design requirements and a long meeting of brainstorming and testing various ideas for different variables in Excel, our group decided on a design for our first oven. The cooking chamber of our first oven was 12cm x 12cm x 7cm. This was to meet the design requirement of having a chamber equal to $1000cm^3$ and minimum dimensions of 5cm. We thought that having a window size somewhere in between the maximum of 14cm x 14cm, and the minimum of 5cm x 5cm would be ideal. When tested in Excel, this size of window produced a satisfactory maximum temperature.

For the outside box, we decided to have 6 cm of insulation on all sides. This meant an outside box with dimensions of 24cm x 24cm x 13cm. We noticed on Excel that increasing the box size by any more than this created a very small difference in the overall temperature of the oven, which is why we decided on only 6cm of insulation. Furthermore, we used wadded newspaper for insulation.

We used octagonal reflectors with an M/L value of 3:1. Octagonal reflectors would generate less heat than trapezoidal reflectors, but would make our predicted temperature more accurate, which is what we wanted. The reflectors were comprised of four rectangles that were 36cm long with a base of 14cm and four triangles with height of 36cm base 14cm. The reflectors were attached to the oven at an angle of 79.69 degrees.

Our cooking chamber was accessed by removing the window and the reflectors. For this design we had the window attached directly to the window. Our thinking was that on test day we would place the biscuit inside the chamber, place the reflectors and window on top and attach the two pieces with duct tape. This is where we lost a lot of heat during the test. The duct tape began to melt and not only did we lose heat, but the reflectors and window began to shift and move during testing. We had to keep adding more and more duct tape and adjusting them throughout the test, which was not ideal.

We did not have a positioning device included in the design of the oven, but we brought a protractor on the day of the test to ensure that the angles were ideal and correct. Had we included a positioning device in the actual design of our oven, these angles may have been more accurate and increased the overall temperature and accuracy of our oven. We cut a hole through the side of the oven as well as the cooking chamber at about mid-height of the chamber for the thermometer. This was to meet the design requirement that the thermometer reach the inside of the cooking chamber through the side of the oven rather than through the window or in the field of the reflectors.

After the first day of testing, we still liked the overall design of our oven. We decided that redesigning the way we attach the window and reflectors to the oven, and the way we access the chamber would be our main concern. We needed to design a way to access the chamber and attach these pieces that would not result in a large amount of heat loss.

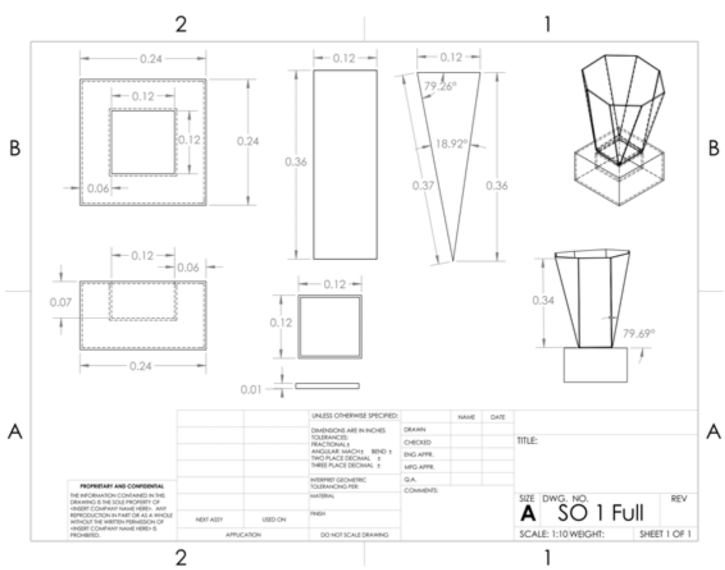


Figure 5: Design of Oven 1

4.2 Oven 2: The Champion

From the first to second oven we did not change much of our design. After meeting and discussing the results from the first test we were overall satisfied with the results from our oven. We knew that if we changed the way we attached the reflectors and window to retain heat, that our oven would perform much better. This was the main change that we made. We focused most of attention on this aspect because even with the heat loss, our oven still reached a maximum temperature of 138 degrees Celsius and the biscuit was still able to be fully cooked.

We increased our cooking chamber to 14cm x 14cm x 5cm. This, again, was to meet the requirements of having a chamber with a volume of $1000cm^3$, and minimum dimensions of 5cm. This also increased the window size of our second oven. We increased the window size to 14cm x 14cm to maximize the amount of sunlight that is able to enter the cooking chamber. We again used 6cm of insulation on all sides, making the outside box dimensions again 26cm x 26cm x 11cm. We again used octagonal reflectors with an M/L ratio of 3:1. The reflectors were comprised of four rectangles the dimensions 42cm x 14cm, and four triangles with height 42cm and base 14cm. We used two sheets of Mylar for the window with 2cm between the sheets. Again, we did not have a positioning device incorporated in the design of our oven. We used a protractor on the day of testing to position of our oven properly.

In our first oven the reflectors and window were separate from the outside box and were attached on the day of testing, resulting in a lot of heat loss where the two pieces were attached. For our second oven, we decided to redesign this. We made the outside box and cooking chamber in one piece, but with no window. The reflectors and window were then attached to each other and attached to a second piece of cardboard of equal size to the lid of the outside box. It would essentially sit snugly on top of the outside box. The attachment had four pieces of cardboard coming down off the sides to grip the side of the outside box to ensure the window and reflectors would not shift during testing, like they did with the first oven.

The other major change we made to our oven was using packing tape rather than duct tape. Because the duct tape melted during our first test and allowed for a lot of heat to escape, we wanted to use a more heat resistant tape for our second oven. We reinforced all parts of the oven with 1 to 2 layers of packing tape in an effort to reduce the amount of heat lost, ideally losing none.

Even with these changes, some heat was still lost where the reflectors were attached to the window, but not nearly as much as our first oven. Even with some heat loss, our oven still worked exceptionally well. Our predicted temperature was 185 degrees Celsius and we reached a max temperature of 182 degrees Celsius, making our oven the best performing oven in our section!

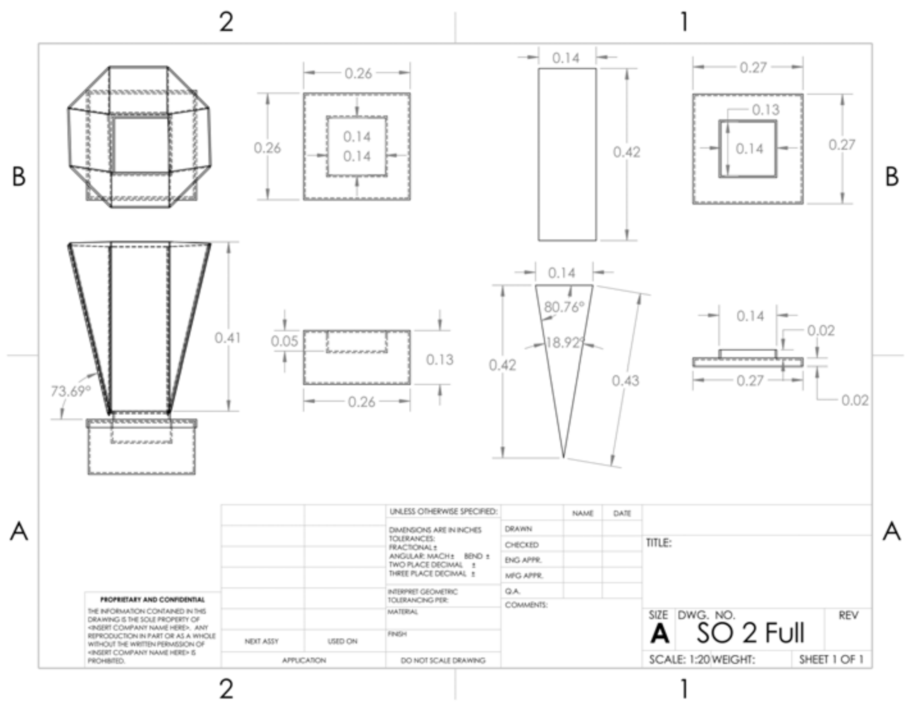


Figure 6: Design of Oven 2.

5 Design Justification

All of our dimensions were designed to fit the outlined design requirements. We were also continuously checking our dimensions in our Excel spreadsheet to see how they would affect our predicted temperature. During both brainstorming sessions we were discussing possible values we could use for all dimensions and then testing them in Excel to narrow down our ideas to one that would work the best. For example, deciding how much insulation we wanted, we tested different amounts of insulation such as 5cm, 6cm, 7cm, and 8cm. We noticed that going beyond 6cm did not retain much more heat, so we decided to use 6cm for insulation. We decided to use wadded newspaper as our insulator thermal conductivity and reference. This type of process was repeated for all the dimensions.

Another thing we were considering when designing out oven was cost. We focused heavily on keeping the cost minimal. This is why we used a smaller M/L value for the first oven. We wanted to use a small amount of resources when designing our oven, so we settled on smaller reflectors. When testing in Excel we decided that these values were the perfect medium to getting a high temperature while still keeping cost lower. When designing out second oven, we decided that increasing M/L and therefore increasing overall cost of our oven was worth it to increase the efficiency and predicted temperature of our oven.

The most major change we made when designing our second oven was the way we attached the reflectors and the window to the outside box. Instead of attaching them on the day of the test with duct tape, we used a Tupperware-style/shoe box lid that had the reflectors and window on top of it. This would allow us to have easy access to the oven chamber, much easier access than with our first oven. This design also helped prevent the massive amount of heat loss we experienced during the first test. Our thinking was that this design would retain heat where the attachment was. This was a successful change because the heat loss decreased drastically from the first to second oven. Not only did it make the oven work more efficiently by better retaining heat, but it made the functionality of the oven better overall because there was easier access to the oven chamber. If used regularly, this oven design makes more logistical sense because the user does not have to reattach the reflectors and window with duct tape each time they would like to use the oven.

6 Test Procedure

The first in-class test took place on 1 October 2019 at 1:00 p.m. on the University of Arizona mall stage. At that time, the ambient temperature, $T_{ambient}$, was $30°C$, and the incident solar power density, I_o, was $980W/m^2$. Our predicted internal oven temperature, T_{io}, was $178°C$. Our testing set-up included our solar oven prototype (nicknamed Cindy), wireless thermometer, phone with Bluetooth, cooking rack, raw biscuit, backpacks, and a water bottle. We used our backpacks and water bottle to prop our oven at the proper angle, where the side of our outer box was 40° off the ground. This angle is complementary to the angle of the sun's rays with respect to the ground, allowing the sun's rays to enter our oven at a 90° angle. We used the shadow our oven created to make sure our oven was always facing the sun directly. Our first oven did not have an efficient attachment mechanism between the reflectors with the window and the oven itself, so we struggled to keep the reflectors on and the heat inside. Another issue we found was that we did not maximize or window area and minimize the depth of the cooking chamber. Due to these issues, we did not reach as high of a temperature as we could have. At the end of the testing period, the maximum temperature our oven reached, T_{io} actual, was $138.9°C$.

The second test, the actual Solar Oven Throwdown, occurred on 18 October 2019. This test also took place on the University of Arizona mall at 1:00 p.m. The ambient data at the time we started testing was as follows: $T_{ambient} = 27°C$ and $I_o = 974.3W/m^2$. According to these factors, our predicted T_{io} was

$185.4°C$. Our final testing set-up was made up of our final oven (nicknamed Cindy Lou Two), wireless thermometer, phone with Bluetooth, cooking rack, raw biscuit, and backpacks. We used the backpacks to prop our oven to the correct angle, again making our oven side 40° off the surface of the ground in order make a 90° angle with the sun's rays. We also reused our method of using the shadow to indicate that our oven was directly facing the sun. This time around, our oven had a secure "shoe-box" attachment mechanism, but the wind became a complication, as it would move our oven over time, causing our angle and direction to be off. Throughout the testing period, we had to slightly adjust our oven to keep the reflectors and window in the ideal position. At the end of the final test, our maximum temperature reached was $182.5°C$.

Figure 7: Our first oven right after construction.

Figure 8: Our second oven cooking during the SOTD.

7 Test Results

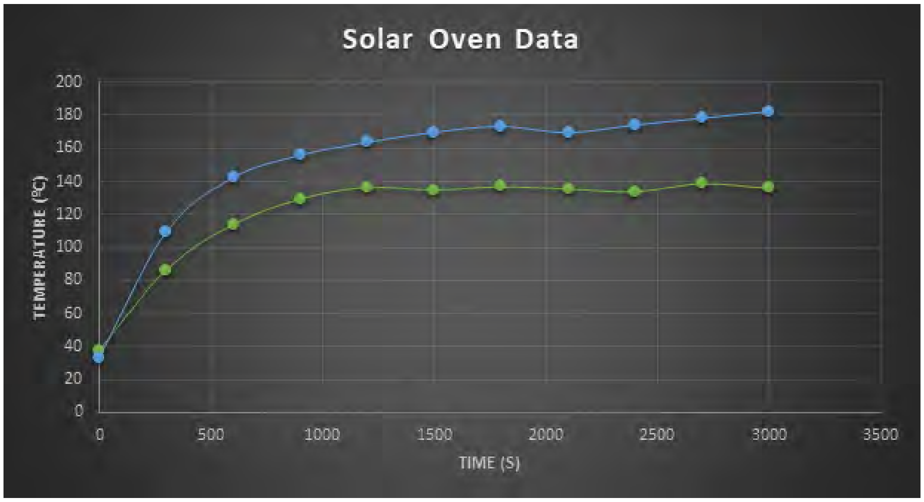


Figure 9: Results from the first (green) and final (blue) tests.

first test	
Time (s)	Temp (ºC)
0	37.81446
300	86.55146
600	114.2205
900	129.3262
1200	136.5372
1500	134.95
1800	137.03
2100	135.5608
2400	133.8664
2700	138.9345
3000	136.0879

Figure 10: Data Table from Test 1

second test	
Time (s)	Temp (ºC)
0	33.18537
300	109.5595
600	142.5457
900	155.9338
1200	164.0317
1500	169.9881
1800	173.5065
2100	169.8429
2400	174.3913
2700	178.424
3000	182.4617

Figure 11: Data Table from Test 2

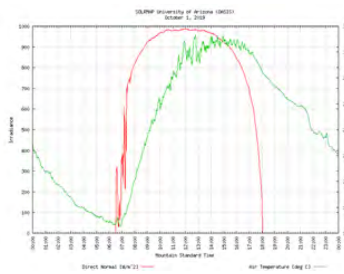


Figure 12: T_{io} from Test 1

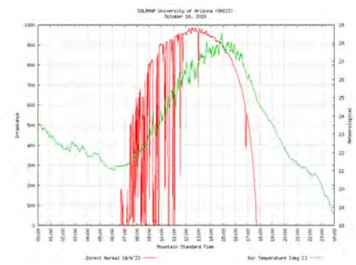


Figure 13: T_{io} from Test 2

7.1 First Test

For our first oven, the test results differed greatly from the predicted temperature value, with a difference of $39.1°C$. The main reason for this large inaccuracy was escaping heat. The joint where our reflectors and window met the oven's cooking chamber was not well constructed, and it was being held together by duct tape. This duct tape was of low quality and began melting soon after the test began. About halfway into the testing period, the reflectors were becoming unattached to the oven and had to be adjusted every couple of minutes. The I_o value remained constant throughout the testing time, and there was no wind or other disturbances. These conditions were ideal to make our predictions accurate if the heat did not escape our oven. When designing our final oven, we knew we had to maximize the window area and create a better way to attach the reflectors. We decided to create a "shoe-box" lid with the reflectors and window attached. This way, there would be no gap between the lid and the oven chamber, and there would be no need for tape to keep the heat inside.

When designing our final oven, we knew we had to maximize the window area and create a better way to attach the reflectors. We decided to create a "shoe-box" lid with the reflectors and window attached. This way, there would be no gap between the lid and the oven chamber, and there would be no need for tape to keep the heat inside.

$$PI_{SOTD} = 3.464 \qquad PI_{COST} = 16.6$$

7.2 Final Test

As our results show, our changes in design brought our results much closer to our predicted value with only a $2.9°C$ difference. The final oven had minimal heat loss. The only issues present on this day were wind and clouds. The clouds caused the Io value to shift right before the testing period started, and the wind changed our oven's angle, making it difficult to keep the oven facing the sun directly at all times. If we were to make another attempt, we could create a stand that would hold it in place better than backpacks. Compared to our first oven, the final reached higher temperatures but had the same trend over time. It took the same amount of time to reach equilibrium in both tests. This shows that the only major design difference that helped our second oven was the new lid that trapped heat inside.

$$PI_{SOTD} = 46.8 \qquad PI_{COST} = 21.30165$$

8 Team Dynamics

Throughout this project, our team was collaborative and effective. Every member did the tasks expected of them, and we communicated clearly and openly about our tasks, ideas, and concerns. As the group leader, Batya oversaw the planning and organization of meetings. She worked with the group to set days and times that worked for the majority, if not all, members. Logan was the designated supplies collector. He gathered the supplies we were given and stored them for the team. Batya also collected some of the extra supplies needed from the store, and Karson provided the aluminum foil. Casey provided supplies such as pens, scissors, etc. for the team. When it came to the design and building of the oven, it was an evenly divided effort. Every team member had a part in measuring, cutting, and putting together the parts of the oven. Karson was our head of Excel, producing our final prediction model, offering many suggestions and solutions, and calculating the predicted temperature and performance indices for the first test. He double-checked all the factors of the oven to make sure we got the results we wanted. For the second test, Batya took over with the prediction model, as Karson was absent. During testing, Casey was the head of data collection. She recorded the temperature values and paid attention to the trend of the temperature. She noticed when we would begin decreasing early, meaning we needed to adjust our angle or make another small change. Logan was often the one to make these adjustments, checking the angle of the oven with respect to the ground and the sun. For the final, report, again, the effort was divided equally among members. Everyone completed the parts they were assigned, and Karson collected and formatted the work into the final document.

9 Design Critique and Summary

While there were a few flaws in our original design, most were fixed by the final test. Our oven construction was solid, and there was no heat leaking from the oven itself. The insulation was packed tight, and the box was put together with no gaps or openings. Our reflectors could have been cut more accurately, but they were extremely close to the right measurements. Once we implemented the “shoe-box” lid design, there was minimal heat escaping from the attachment of the reflectors and the oven itself. The window was maximized and accurate, and our two Mylar sheets were approximately 1 cm apart, giving us the ideal U_w values. The only design change recommended would be a sturdier way to support the oven so that the wind does not affect the angle while testing.

Our team dynamics worked very well for us. We were very relaxed and open with each other. If one person had more work than the others, it was volunteered and not forced. If we were to change anything, we might have put all data, measurements, and other important details into a document we all had access to. This way, we could all see the work at any point. We would have also tried to test the oven prior to the first in-class test.

For future teams, we would recommend listening to and discussing all ideas. The first answer is not always the best one. Make sure you follow all guidelines and maximize/minimize values as needed. Be careful and accurate with your measurements. Double check your prediction models, and make sure all values and equations are put in correctly.

10 References

[1]https://midcdmz.nrel.gov/apps/sitehome.pl?site=UAT
[2]https://d2l.arizona.edu/d2l/le/content/786851/Home
[3] https://www.walmart.com/ip/Scotch-Heavy-Duty-Shipping-Packaging-Tape-1-88-in-x-54-6-yd-1-Pack/21175897
[4]https://energy.arizona.edu/
[5]Temperature-dependent heat transfer coefficient for Mylar glazing (Johnson, 2003)

11 Appendices

11.1 Mylar Thermal Coefficients

Table 1. Temperature-dependent heat transfer coefficient for Mylar glazing

T_{io} (°C)	$U_{w,\,single}$ (W/m^2·°C)	$U_{w,\,double}$ (W/m^2·°C)*
66	10.10	4.88
93	13.90	6.69
121	18.66	8.96
149	24.34	11.74
177	31.60	15.20
204	40.11	19.35

*based on 1–2 cm gap between Mylar sheets for two layers of Mylar (Johnson, 2003).

11.2 Our Recommendations to 'Who 8 the Biscuits'

Solar Oven Dissection Questions

Dissecting Team: #7 Totally Baked

Team whose oven is being dissected: #8 Who 8 the Biscuits

T_{io} predicted: 201.7

PI: 2.92

Before Disassembly:

1. Describe the oven in general terms.
   a. It is a box within a box with four trapezoidal reflectors meeting at the corners
2. Picture of the oven
   a. 
3. Describe the appearance of the oven exterior
   a. The oven exterior is just the cardboard with duct tape on the seams.
4. What are the outside dimensions, including the oven window and reflectors?
   a. Dimensions of the outer box: 24x24x17 cm^3
   b. Area of window: 14x14 cm^2
   c. Dimensions of reflectors: height=42 cm
5. Describe the reflectors? How many? Shape? Where do they meet? How smooth is the aluminum foil?
   a. There were four trapezoidal reflectors. They met at the corners and attached to the window evenly. The foil was very smooth.
6. What is M/L?
   a. 3
7. Describe the omega angle for the M/L? Is it correct?

a. 80°

8. How and where is the thermometer inserted?
    a. It was inserted through the side of the outer box and oven chamber.
9. How is the cooking chamber accessed and what type of rack is used?
    a. The window and reflectors detached from the oven to access the cooking chamber. The rack was made of cardboard.
10. How is the oven aligned with the sun?
    a. The oven itself stood straight up. We assume they used external resources to prop their oven at an angle.
11. Any other external characteristics?
    a. None that stand out

During Disassembly:

1. Preserve the reflectors (if any), if the team would like to reuse them for their final oven.
2. Describe the internal characteristics of the oven in general terms.
    a. The oven chamber was black and surrounded by wadded newspaper.
3. What are the inside dimensions, including the interior cooking chamber dimensions, all wall thicknesses, and the thickness of the insulation? Are the dimensions uniform in every direction?
    a. Cooking chamber dimensions: 14x14x5 cm^3
    b. Wall thickness: 4 mm
    c. Insulations thickness: 12 cm
    d. All dimensions were uniform
4. What materials are used and in what way? For example, is the oven chamber made from cardboard and coated with foil or painted black?
    a. The chamber, outer box, and reflectors were made of cardboard. Everything was put together with duct tape. The oven chamber was covered in black construction paper, and the reflectors were covered in aluminum foil.
5. How many layers of window glazing are used, how wide is the air gap between the layers, and what is the window material?
    a. 2 mylar layers
    b. 1-2 cm
6. Describe the insulation. If newspaper was used, is the newspaper loosely or tightly packed?
    a. The newspaper was tightly packed.
7. What is used to join the pieces of the oven together?
    a. Duct tape was used to join everything.
8. Record any other pertinent information regarding the internal characteristics of the oven.
    a. Nothing of import.

After Disassembly:

1. Return the reflectors to the team.
2. What are the strengths and weaknesses of the oven?

a. Strengths: Their design of the oven itself and the tightly packed insulation were very impressive and effective. The reflectors were very smooth, which would be a positive. Overall, intelligent design and effective ideas.
b. Weaknesses: The tape joint attaching the reflectors to the oven most likely leaked heat, which would have lowered their PI. The use of trapezoidal reflectors, while increasing temperature, will cause their prediction to be less accurate than if they used octagonal.

3. To what do you attribute the performance (good or bad) of the oven during the testing?
   a. They had very compact insulation and smooth reflectors, which helped the oven. Their design was strong (M/L and window area were maximized), and their oven and reflectors were built well. However, they likely had the same issue we did where lots of heat was escaping where the reflectors connect with the rest of the oven. There could also have been discrepancies in their PI because of their use of trapezoidal reflectors instead of octagonal.
4. Based on your findings, what can you recommend about building solar ovens?
   a. Our main recommendation would be to change the way the team connects the reflectors to the oven. This was likely an area where a lot of heat was lost and designing a new way to have them connect will greatly increase the efficiency of the oven.

11.3 Recommendations from ‘The SNACCS That Smile Back’

Sophia, Natalie, Megan, Alex, and Alex 10/3/19

Solar Oven Dissection Questions

Solar Oven Dissection Questions

Before Dissasembly:

1. Describe the oven in general terms. **The Box is small, cubic, well built, and the cooking chamber is a small box in the middle. Inside, there is a significant amount of newspaper insulation. It is made of cardboard with black tape holding it together. The tinfoil reflectors are octagonal and have very reflective tinfoil.**

2. Draw a sketch of the oven. Additionally, you may want to include a photo of the oven.

3. Describe the appearance of the oven exterior. **The oven is unpainted, held together with black tape along the seams. It is held together extremely well and very strong, appearing to be very well sealed.**

4. What are the outside dimensions, including the oven, window, and reflectors:

   a. **Oven: 11.5 x 11.5 x 6.5 cm (cooking chamber), 25 x 25 x 13 cm (exterior)**
   b. **Window: 11.5 x 11.5 cm**
   c. **Reflectors: 35.6 cm tall, 11.5 cm base, 28.5 cm top**

5. Describe the reflectors: **The reflectors are octagonal, made of cardboard, and connected to each other by red tape. The tinfoil is very shiny and smooth.**

6. What is M/L? **35.6/11.5 = 3.10**

7. Describe the omega angle for the M/L. **110 degrees. This is roughly the correct value.**

8. Where is the thermometer inserted? **It is inserted through the side of the box, into the cooking chamber.**

9. How is the cooking chamber accessed and what type of rack is used? **The reflector would hinge off of the cooking chamber, and the rack was a cardboard ring with mylar.**

10. How is the oven aligned with the sun? **The oven is aligned by hand and by placing materials below it to hold it up. There is no dedicated alignment mechanism.**

11. Other pertinent information: **The oven was overall well built with good insulation. The stats were not absolutely perfect and the reflector came already detached from the oven.**

During Disassembly:

1. Preserve the reflectors if the team would like to reuse them for their final oven.

2. Describe the internal characteristics of the oven in general terms. **The interior of the oven was packed very tightly with newspaper for absolute maximum insulation. The cooking chamber was attached robustly to the top of the insulation box. The cooking chamber itself was solidly built. Overall the interior was also well built.**

3. What are the inside dimensions, including the interior of the cooking chamber, all wall thicknesses, and the thickness of the insulation? **The box itself was 25 x 25 x 13 cm, the cooking chamber was 11.5 x 11.5 x 6.5 cm. The cardboard insulation was 0.4cm for each layer. The insulation was 9 cm thick. The dimensions were all very consistent.**

4. What materials were used in what way? **Cardboard made up the main body of the oven. Black paper was used inside the cooking chamber in order to absorb more heat from the sunlight. Tinfoil was used on the reflectors to reflect extra sunlight into the cooking chamber. Lastly, tape was used to hold it all together.**

5. How many layers of window glazing are used, how wide is the air gap between the layers, and what is the window material? **Two sheets of mylar were used for the window with a 1cm gap between the layers.**

6. Describe the insulation. If newspaper was used, is the newspaper loosely or tightly packed? **The newspaper used was packed, quite literally, as tight as possible.**

7. What is used to join the pieces of the oven together? **Tape is used to join everything in the oven together, with varying colors of tape (black, red, and blue).**

8. Other pertinent information: It is. **built well and complies with most specifications. Not too much of concern.**

After disassembly:

1. Return the reflectors to the team.

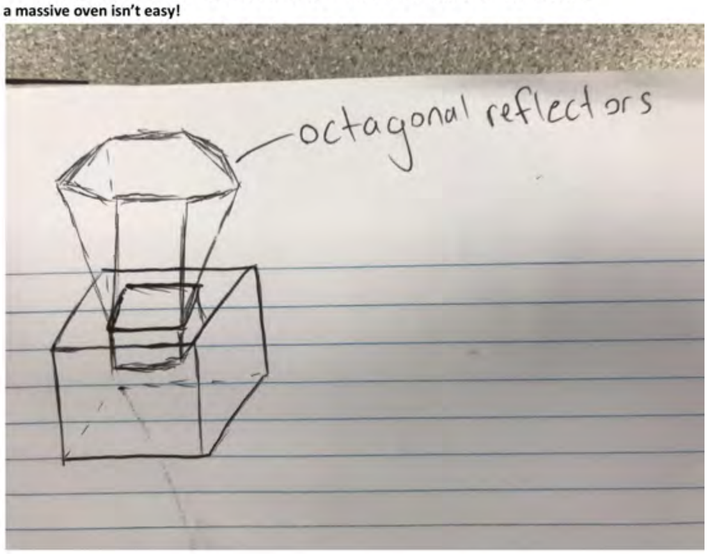
2. What are the strengths and weaknesses of the oven? **The oven's main strength is how well built it was. Tilting it over and transporting it are not things to worry about when dealing with the oven. Another strength is that due to its small size, it is easy to transport. Also, its tightly packed newspaper insulation provides significant protection against escaping heat. Some of its weaknesses include that it's cooking chamber and window size is not optimized, as the height can be shorter, and the window can be larger. Another issue is that while the oven itself is built very well, its reflector was not attached particularly well, and combined with the fact that the mylar window is connected to the reflector, this allowed for a significant amount of heat to escape.**

3. To what do you attribute the performance (good or bad) of the oven during testing? **The solar oven's good performance is due to its high amount of insulation, it's good build construction, and it's decent reflector design. This allows heat to enter and stay in the oven efficiently, leading to increased temperatures. However, it's unoptimized chamber design means that maximum heat cannot enter the chamber for its size, as the window size is smaller than it can be. This also means that the reflectors are not as large as they could be, limiting their effectiveness. In addition, the poor connection of the reflectors to the cooking chamber, and with it, the mylar windows, allows for a significant amount of heat to escape the oven that could easily be retained.**

4. Based on your findings, what can you recommend about building solar ovens?

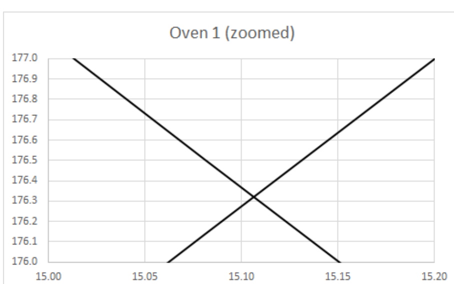
    a. **Ensure your solar oven is optimized for its allowed specifications. Unless you are going cheaper, it is best to try to maximize the area of the window using the dimensions of the cooking chamber, which also allows for the optimization of the reflector design.**
    b. **Make your oven well built and be sure that your insulation is enough for keeping heat inside of the oven.**
    c. **Make sure ALL gaps are sealed. Any unsealed gaps can result in significant heat loss, and this will likely be the main cause of deviations in predicted vs actual temperatures.**

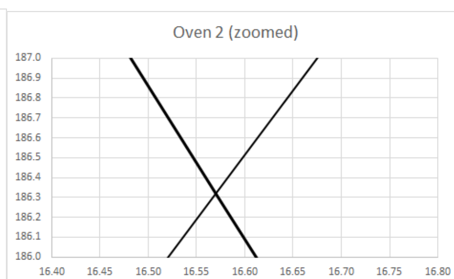
d. **Consider logistics when building your oven, we learned the hard way that transporting a massive oven isn't easy!**



11.4 Data from our Excel Prediction Model

Solar Oven Comparisons				
Param.	**Oven 1**	**Oven 2**	**Units**	**Description:**
Fixed Input Parameters				
τ	0.92	0.92		transmissivity for a single layer of Mylar
a	0.9	0.9		absorption factor of oven chamber and contents
r	0.7	0.7		
$V_{chamber}$	0.001	0.001	m^3	volume of the oven chamber
Variable Input Parameters				
$T_{ambient}$	21	21	°C	ambient temperature
I_o	1000	1000	W/m^2	solar power density
θ_s	44	44	°	angle of the sun's rays with respect to the ground
β	46	46	°	angle of the top surface of the oven with respect to the ground
Design Input Parameters				
L	0.12	0.14	m	length of oven window
W	0.12	0.14	m	width of oven window
n	2	2		# of layers of mylar
M/L	3	3		ratio of reflector length to window length
Calculated Input Parameters				
A_w	0.0144	0.0196	m^2	area of the window
A_{sb}	0.047733	0.048171429	m^2	area of the sides and bottom of the cooking chamber
h	0.069444	0.051020408	m	height of oven chamber (>5)
U_{sb}	1.881453	1.440702782	$W/(m^2{*}°C)$	heat transfer coefficient for the sides and bottom of the cooking chambe
M	0.36	0.42	m	length of the reflectors
α	16.30655	16.30654852	°	angle of sunlight with respect to the reflectors
Ω	106.3065	106.3065485	°	lid angle
G	4.351848	4.351847733		gain from adding octagonal reflectors
Variables for Heat Transfer Coefficient Calculation				
x1	0.004	0.004	m	inner cardboard wall thickness
x2	0.05	0.07	m	insulation thickness
x3	0.004	0.004	m	outer cardboard wall thickness
k1	0.064	0.064	W/(m*°C)	inner cardboard wall thermal conductivity
k2	0.123	0.123	W/(m*°C)	insulation thermal conductivity
k3	0.064	0.064	W/(m*°C)	outer cardboard wall thermal conductivity
Cost-Based Performance Index				
Weight	1.256350	1.690037	lbs	approx. weight - likely an underestimation
Foil	0.257991549	0.351155164	m^2	amount of foil used
# paper	1	2		pieces of black paper used
cardboard	0.454803	0.611441	m^2	amount of cardboard used
labor	5	5	$	fixed cost of labor
PI_{cost}	24.00963	23.08284		approx. cost based performance index
Predicted Output				
T_{io}	176.32	186.3	°C	predicted internal oven temperature





11.5 Data Collection Sheet: Test 1

Preparation for the Solar Oven First Test

Team Name: Totally Baked

Prior to the test:

- Weigh your oven (in grams) and record it here: 103.0682 grs
- Write your team name on your oven
- Bring a laptop with the Oven Prediction Excel spreadsheet in it
- Bring a protractor to measure angles
- Bring the thermometer
- Don't forget to bring your oven with you ☺
- I will provide a biscuit to bake. Your oven needs to have a rack inside the chamber to hold the biscuit.

On the test day:

- Go to the designated testing location
- Place your oven facing directly to the sun
- Use a protractor to measure the angles for the spreadsheet inputs
- Obtain $T_{ambient}$ and I_o from the instructor and write them on your oven and record them here:
  $T_{ambient}$: 30°C I_o: 980 W/m²
- Calculate and write your predicted T_{io} on your oven and record it here:
  T_{io} predicted = 178°C
- Record T_{io} from the Vernier thermometer by using your iPhone
- When your oven chamber reaches steady state (max temperature), write T_{max} on your oven and record it here: T_{max} : 138.9°C
- Calculate PIs for the test:

Solar Oven Throw Down PI:

$$\boxed{PI_{SOTD} = \frac{T_{actual}}{\left|T_{actual} - T_{predicted}\right| + 1} = \frac{T_{actual}}{\Delta T + 1}}$$

PI SOTD = 3.464

Cost-based PI:

$$\boxed{PI_{cost} = \frac{T_{actual} - T_{ambient}}{\text{Cost}}}$$

PI cost = 16.6

Scan and submit this page to me via email ASAP.

Solar Oven Testing Data Collection

Team Name: Totally Baked

Date: 10/1/19 Start Time: 1:00

Forecasted Ambient Air Temperature at start of test: 30°C

I_0 at start of test: 980 W/m²

Predicted Oven Interior Temperature during test: 178°C

Internal Oven Temperature at 5-minute intervals:

Time	Temperature (°C)
1:05	86.6°C
1:10	114.2°C
1:15	129.3°C
1:20	136.5°C
1:25	135°C
1:30	137°C
1:35	135.6°C
1:40	133.9°C
1:45	138.9°C
1:50	136.1°C

Highest temperature reached during test: 138.9°C

Signature(s) of data recording engineer(s):

[signature]

[signature]

Solar Oven Throw Down Performance Index:

$$PI_{SOTD} = \frac{T_{actual}}{\left|(T_{actual} - T_{predicted}\right|) + 1} = \frac{T_{actual}}{\Delta T + 1} = 3.464$$

11.6 Data Collection Sheet: Test 2

Solar Oven Testing Data Collection

Team Name: Totally Baked

Date: 10/18/2019 Start Time: 1:00PM

Forecasted Ambient Air Temperature at start of test: 27°C

Io at start of test: 974.3

Predicted Oven Interior Temperature during test: 185.4°C

Internal Oven Temperature at 5-minute intervals:

Time	Temperature (°C)
1:00	33.2
1:05	109.6
1:10	142.5
1:15	155.9
1:20	164.0
1:25	170.0
1:30	173.5
1:35	169.8
1:40	174.4
1:45	178.4
1:50	182.5
1:55	

Highest temperature reached during test: 182.5

Signature(s) of data recording engineer(s): [illegible]

Solar Oven Throw Down Performance Index:

$$PI_{SOTD} = \frac{T_{actual}}{\left|(T_{actual} - T_{predicted}\right| + 1} = \frac{T_{actual}}{\Delta T + 1} = 46.8$$

11.7 PI_{COST} Calculation for Final Oven

Cost-Based Performance Index			
Weight	1.750000	lbs	weight - -20 cents per pound
Foil	0.351155164	m^2	amount of foil used - $0.55 per square meter
mylar	2		number of mylar sheets used - 25 cents each
# paper	2		pieces of black paper used - 3 cents each
cardboard	0.644820	m^2	amount of cardboard used - $1.75 per square meter
tape	5.000000	m	meters of tape used - 12 cents per meter
labor	5	$	fixed cost of labor
PI_{cost}	21.30165		cost based performance index
Predicted Output			
T_{io}	182.5	°C	predicted internal oven temperature