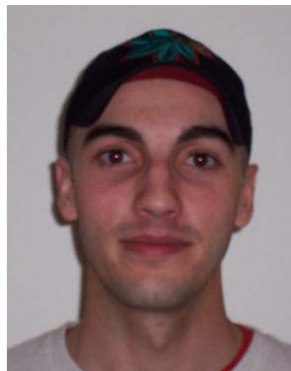


Final Report: Improved Solar Cooking Unit for Use in Third World Countries

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Introduction

Currently in third world countries, a task as simple as cooking has important consequences. Indoor pollution issues and scarcity of available firewood present dangers as well as obstacles. One solution to these cooking issues is the use of solar energy for food preparation. One solar cooking unit currently in use is a cardboard panel cooker called the Cookit.

Although it is an effective design, the Cookit has certain flaws that could be improved in a new design. We propose to design a solar cooker to improve upon and replace the Cookit model currently found in many homes in third world countries. Specifically, corrugated plastic will be investigated as a replacement material for cardboard. We are focusing on seven main criteria for the design including cost, cooking efficiency, portability, structural stability, water resistance, ease of use, and aesthetics. By focusing on these criteria, we will address flaws in the Cookit design while maintaining its optimal characteristics.

Problem Statement/Design Specifications:

The interior surface of the design must achieve an acceptable measure of reflectivity. The device itself must be portable both for shipping to the customer and for transport by the user. Though low weight must be maintained for portability, the design must be capable of withstanding the force of wind. The design must also incorporate water resistance such that it will not be destroyed by rain or heavy dew. The device must be easy to set up and take down as well as to use. It is preferable that these basic tasks be explicable via simple pictorial instructions only. Finally, the design must be low cost but should still be as aesthetically pleasing as possible.

On February 15, 2007, we received word from Dr. Dale Andreatta that the current Cookit is no longer being produced. Solar Cookers International lost their source for reflective

cardboard material when the company that produced this material went out of business. We have since learned that Solar Cookers International is now heavily considering the use of corrugated plastic in their replacement unit. This development represents an opportunity for our project to have an immediate real-world impact provided we develop a successful design.

Fold Methods

Last quarter we experimented with the corrugated plastic in order to understand various methods of folding. Specifically, we considered three methods: hand folding, folding with the aid of a break press, and folding with the aid of partial cutting. The first method tested, hand folding, proved to be the most infeasible. This method required the most effort while also making it difficult to precisely adhere to desired fold lines. These problems were magnified if the desired fold was not in the same direction as the corrugations in the material. Furthermore, once made, the fold was not very strong and the material tended to return to its initial form. This spring like action would result in a considerable decrease in the portability of our design.

The next method tested was folding with the aid of a break press. A significant improvement over hand folding was observed, but this technique is still not ideal. The corrugations were more compressed versus hand folding and folds could be easily made against the grain of the corrugations. However, the material still had a strong tendency to return to its initial form.

The final method tested last quarter was a partial cut folding technique. This method involved cutting through one surface and the corrugations of the corrugated plastic leaving only the second surface of the material fully intact. This cut allows the material to fold in the direction of the uncut surface. This method was selected for our 5mm design because cutting the material prior to folding allowed for very precise fold lines based on the precision of the cut.

Once cut, the folds held their shape much more readily than in the pure folding and break press cases. The nature of using a partial cut technique presents a pinch hazard. Although it is just plastic this is still a concern with the 5mm design and would need to be addressed if this method was chosen.

A technique to reduce the spring back tendency of the plastic and to avoid a folding technique with a pinch hazard was discovered after talking with Amatech-Polycel, the supplier from which the 3mm corrugated plastic was obtained. Amatech-Polycel recommended pounding a steel plate with a mallet to form the fold creases. On our 3mm prototype we first used the break press to establish and start the folding lines, we then used a small steel plate and a mallet to try and define the creases better. Only a small steel plate of the width we desired could be found and this presented a few problems. The corners of the plate were not rounded so the corners needed to be placed on paper shims to keep from gouging the corrugated plastic. Ideally we would have liked a long piece of steel stock that could have been held in place as someone worked back and forth repeatedly to create the creases.

Using this new combination technique provided one major benefit. The technique allowed use to make the 3mm prototype fold like the Cookit, a huge benefit compared to our other prototype, which folds into a bucket shape. The bucket shape allows for some weight to be carried while transporting to the cooking site, however, it is not as compact as the folding version. Allowing the corrugated plastic cooker to fold like the Cookit, a widely used solar cooker means that the same simple pictorial folding guide could be used. This also means that current customers could easily transition from using the current Cookit to the water resistant corrugated plastic. In order to verify that the 3mm corrugated plastic was strong enough a strength test needed to be performed, similar to those performed last quarter with the 5mm

design. Sample test pieces of 1"×2" were made so that the corrugations would be perpendicular with the pulling direction of the Instron machine. The results of this test and more detail about the testing procedure can be seen in the "Material Strength Testing" section of this report.

Solar Heat Testing Procedure

One of the most important tests we ran this quarter was the solar heating test. This test was very important because the experiment exactly replicated how the solar cookers would be used in the third world countries they are intended for. This test was conducted multiple times throughout the quarter with slight variations each time. However, the overall procedure remained the same. All of these tests were conducted over a matter of hours at SEA Limited in Columbus, Ohio, where Dr. Dale Andreatta was gracious enough to take data readings throughout the experiment. We went to the site for each test in order to set it up and take the initial readings, and Dr. Andreatta took any additional readings after that. He then sent us the results at the conclusion of the test.

The testing procedure involved two solar cookers, two black pots, two covers, clips, zip ties, a voltmeter, a pyranometer, thermocouples, and heat resistant tape. We started by taping a thermocouple to the center of each of the two pots, elevated one inch from the bottom of the pot. Next one of the empty pots was weighed to be 386.2 grams using a standard gram scale. We then filled the pot with just enough water to fully submerge the thermocouple and weighed it once again. The other empty pot was then placed onto the gram scale and water was added until both pots reported the same weight. The two solar cookers being tested were then set up side by side on a picnic table located at a corner of the building. This location offered full exposure to the sun while also partially acting as a shield to the wind. Clips were used to hold the cookers in position. The water-filled pots were then carefully placed into their covers and zip-tied shut with

only the thermocouple leads sticking out of the bag. In the experiment involving a tight PFA cover, the bag edges were wrapped underneath the pots rather than being zip-tied shut. The pots were then carefully placed in the center of their respective cookers. A minute or so was then allowed to pass before the initial temperature readings were taken. During this time, the pyranometer was used in conjunction with the voltmeter in order to measure the intensity of the sun. This was simply done to show how peak water temperatures related to peak sun intensity. Once the intensity was recorded, the thermocouple leads were attached to the voltmeter and the temperature was recorded. The rest of the experiment consisted of simply checking the set-up a number of times during the next few hours and reattaching the thermocouple leads to the voltmeter in order to record the temperature. Usually the picnic table had to be rotated once during the experiment in order to have the cookers facing the sun. In order to compare the cookers being tested and draw conclusions, tables and graphs were generated based on the experimental results.

Solar Heat Testing Results

The first test conducted using the procedure explained above took place on April 17th, 2007. For this initial test we compared the standard cardboard CookKit to the 5mm thick corrugated plastic prototype we developed last quarter in ME 564. Pots were covered with the standard plastic bags in both cases. Although last quarter's reflectivity testing showed the two should perform at a similar level, the solar heat test is a much more reliable testing method because it occurs over a few hours rather than a few minutes. The results of this test are tabulated in Table 1 and shown graphically in Figure 1.

Table 1: TEST 1 4/17/07. 5 mm Plastic (Bag) vs. Cardboard (Bag)				
Time	Plastic Temperature (deg C)	Cardboard Temperature (deg C)	Air Temperature (deg C)	Weather
10:13	21.4	22.9		Strong sun, strong wind
11:29	38.6	39.9		Strong sun, strong wind
12:54	69	69.1		Strong sun, strong wind
14:03	77.7	82.5	15	Strong sun, strong wind
14:51	85.2	89.5		Strong sun, strong wind
15:30	85.3	92.3		Strong sun

Note: Units rotated at 14:03

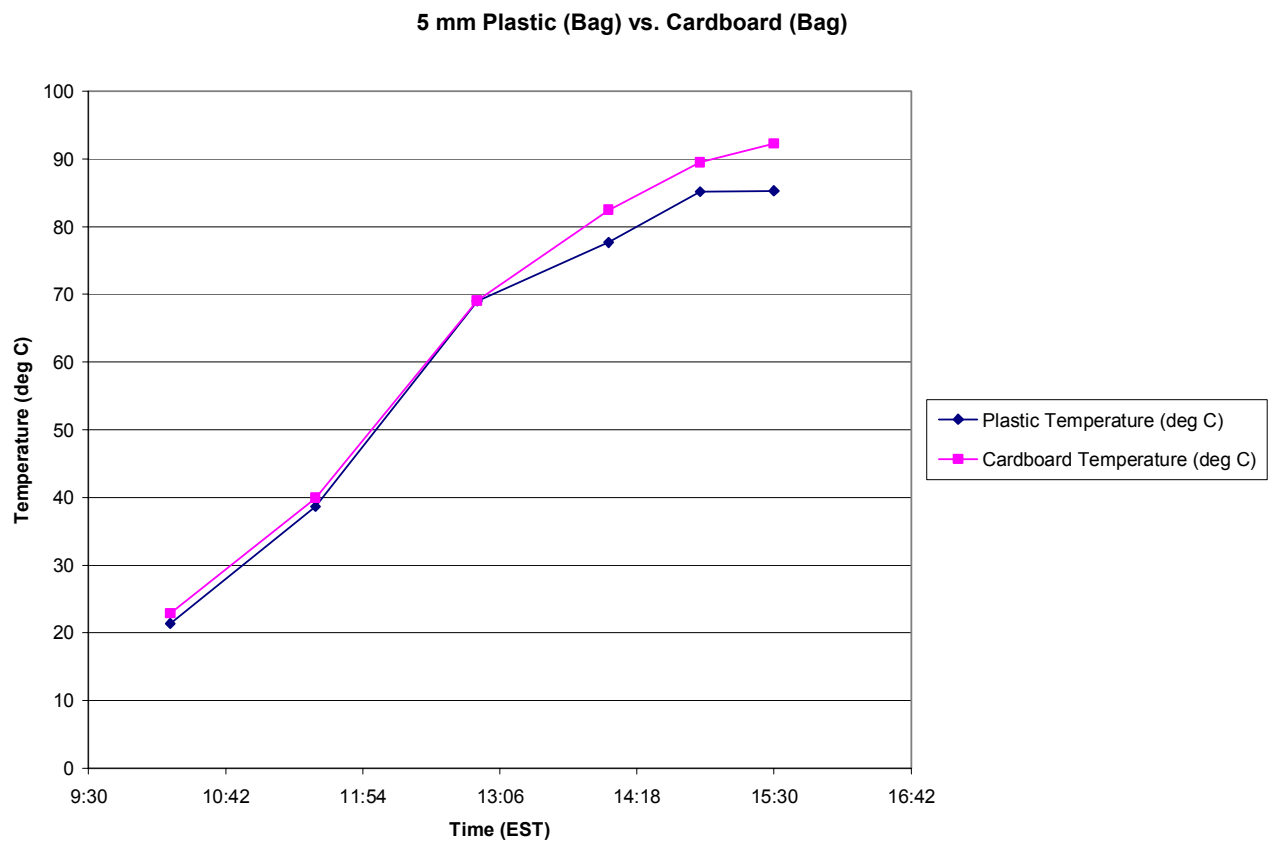


Figure 1: Test 1

The first thing to note about this test was that it strayed from the given procedure in a couple ways since it was the first test conducted. Rather than using just enough water to submerge the thermocouples, a full two-liter bottle was used in both pots. The gram scale method was used in later experiments because less water is more typical of how these cookers would actually be used. Also, the pyranometer was not available and thus was not used in this initial test.

As far as the physical results, the first few readings are very similar to one another, indicating that the reflectivity of the aluminum foil used in our prototype is very similar to that of the aluminized cardboard material used in the CooKit. Over the last few readings when the sun was lower in the sky, the CooKit outperformed the plastic prototype. After further testing and analysis, we would eventually conclude that the reason for this is that the front panel of our prototype stuck up slightly higher than the front panel on the CooKit. Although it was not drastic enough to block the sun's rays completely, it was enough to reflect some of the rays away from the pot rather than directly at it. Further, upon breaking down the experiment it was noticed that the thermocouple in the plastic cooker's pot had come loose, possibly altering the location where the reading was taken. This may have affected results.

Test number two was conducted on May 1st, 2007. For this test we used the same two cookers as the first test. The difference was that this time we replaced the standard bag with a tight PFA plastic cover for the pot contained within the plastic prototype. We continued to use a standard plastic bag with the CooKit. The tight PFA plastic cover adds thermal benefits by allowing for more sunrays to be trapped within the cover and thus be directed at the pot. The goal of the experiment was to see if the added thermal benefits of the tight cover would allow the more durable plastic cooker to perform as well as the standard CooKit and standard bag

technology currently in use. The results are tabulated in Table 2 and shown graphically in Figure 2.

Time	Plastic Temperature (deg C)	Cardboard Temperature (deg C)	Sunlight Intensity (mV)	Weather
10:24	21	23	60	Mostly clear, light wind
11:27	57	58	76	Mostly clear, moderate wind
12:24	74	75	85	Mostly clear, moderate wind
13:15	87	83	90.3	Mostly clear, moderate wind
16:39	65	59	52	Hazy sun, strong wind

Note: Units rotated at 13:18

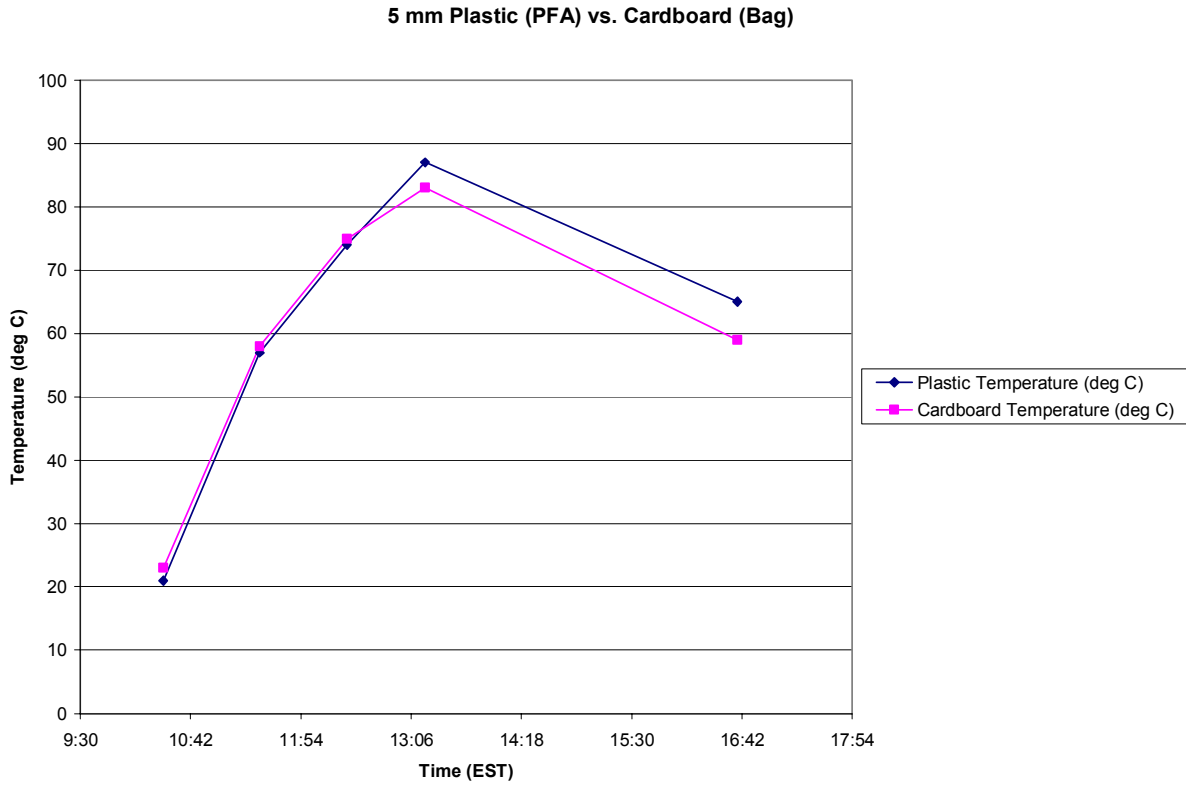


Figure 2: Test 4

The results showed that the plastic prototype along with the tight cover outperformed the standard CookKit with a loose plastic bag. Much more condensation was observed within the loose bag as opposed to the tight PFA cover during testing. This test proved that the plastic design has the ability to perform to an acceptable level in the field.

Our third test was conducted on May 8th, 2007 and was simply a repeat of test number one. As was noted earlier, the procedure for test one strayed slightly from the procedure we wished to use and the thermocouple came loose during that experiment. We wanted to make sure the results we obtained from test one were not due to outside factors such as these. The results of test three are shown below in Table 3 and Figure 3.

Time	Plastic Temperature (deg C)	Cardboard Temperature (deg C)	Sunlight Intensity (mV)	Weather
10:44	17	22	68.9	Strong sun, no wind
12:07	55	61	57	Thin clouds
13:25	72.5	77	88.8	Clear sky, light wind
14:51	85	91	79.5	Clear sky, light wind
15:38	85	90	72	Clear sky, light wind

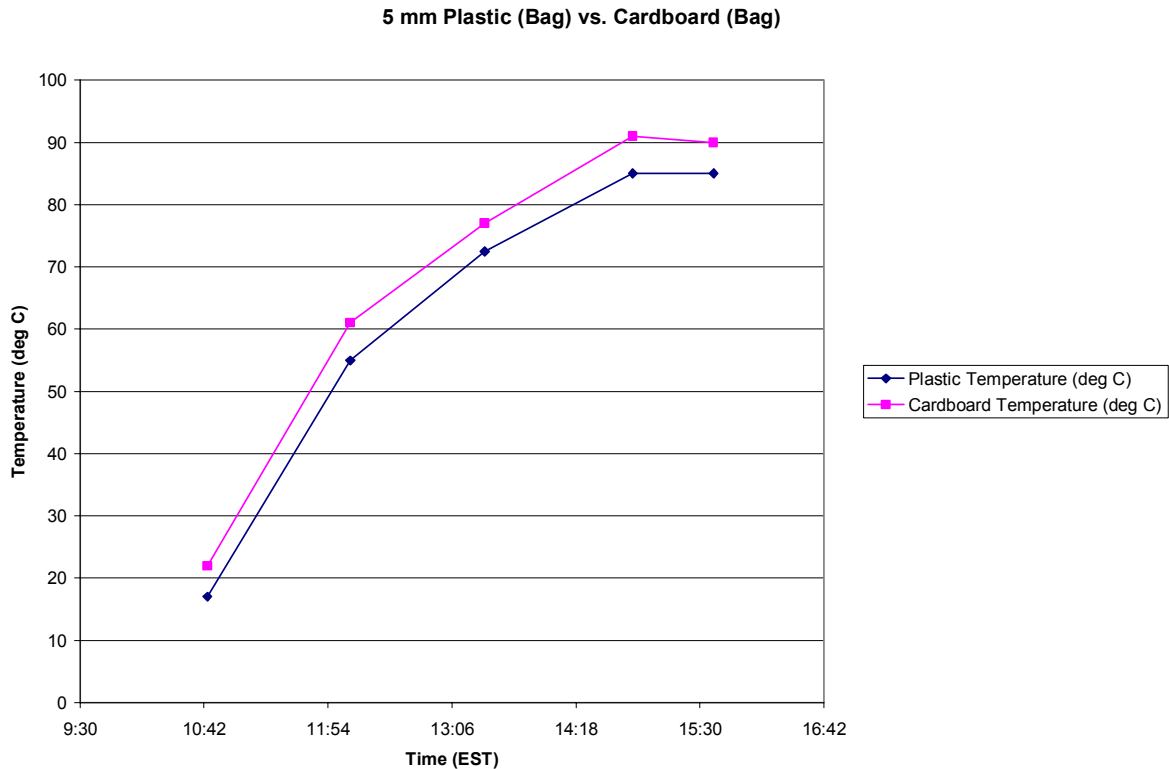


Figure 3: Test 3

The results of the third test were similar to the first one. The cardboard Cookit once again outperformed the plastic prototype. This would further lead us to believe the difference could be attributed to slight variance in the front panel on the plastic prototype. We would attempt to further investigate and fix this variance in future tests. Possible alteration of results in test one due to the movement of the thermocouple was ruled out following test three since its results were similar to test one.

For the fourth test, conducted on May 15th, 2007, we tested out a new plastic prototype. This prototype was made of a thinner corrugated plastic (3 mm vs. 5 mm) and was crudely folded as opposed to cut like the previous prototype. We paid more attention when shaping the front panel on this prototype since we suspected that we had some issues with this panel on the

previous prototype. We set this test up similar to tests one and three. Both cookers had the standard plastic bag. The results are shown as Table 4 and Figure 4.

Table 4: TEST 4 (5/15/07). 3 mm Plastic (Bag) vs. Cardboard (Bag)				
Time	Plastic Temperature (deg C)	Cardboard Temperature (deg C)	Sunlight Intensity (mV)	Weather
10:45	22	23	62	Strong sun, strong wind
12:15	66	67	85	Strong sun, strong wind
13:07	79	76	90	Strong sun, strong wind
14:13	83	80	87.5	Mostly sunny, strong wind
15:08	88	80	86	Mostly sunny, strong wind
15:37	86	79	20.4	Sun behind thick cloud, strong wind

Note: Units rotated at 13:07

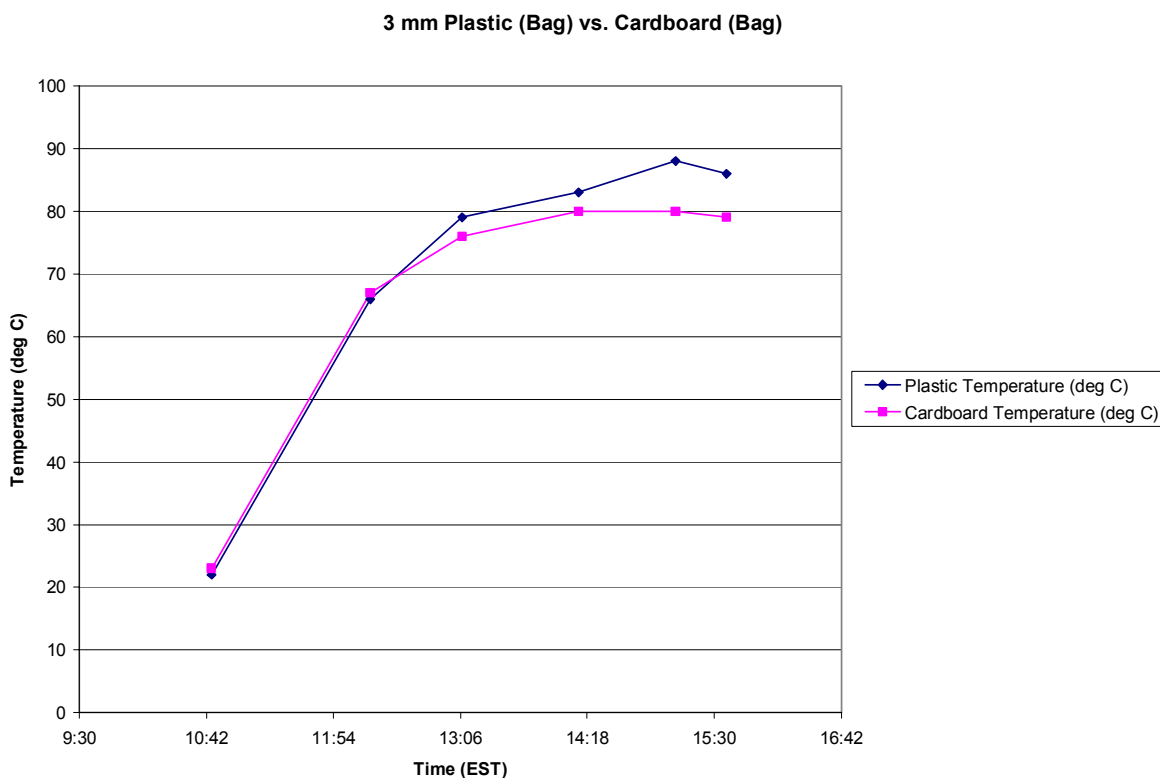


Figure 4: Test 4

The results of this test were very positive. The folded plastic prototype outperformed the cardboard Cookit without the need to use the tight PFA cover. The theory of the poor front panel on the previous prototype gained momentum as the increased performance of the thinner prototype probably resulted from the smaller and more accurate front panel it contained.

The fifth and final test we conducted this quarter for solar heating purposes were conducted on May 22nd, 2007. For this test we compared the new thinner plastic prototype to the older thicker plastic prototype, both using loose bags. Our expectation based on previous testing was that the thinner prototype would outperform the thicker prototype. A result like this would further show that test four was accurate. The results are shown as Table 5 and Figure 5.

Time	3 mm Temperature (deg C)	5 mm Temperature (deg C)	Sunlight Intensity (mV)	Weather
11:03	17	16	71	Strong sun, no wind
12:23	50	48	85	Strong sun, light wind
13:32	72	68	98.5	Mostly sunny, light wind
14:39	74	72	96	Partly cloudy, light wind
15:29	71	67	86.5	Partly cloudy, light wind

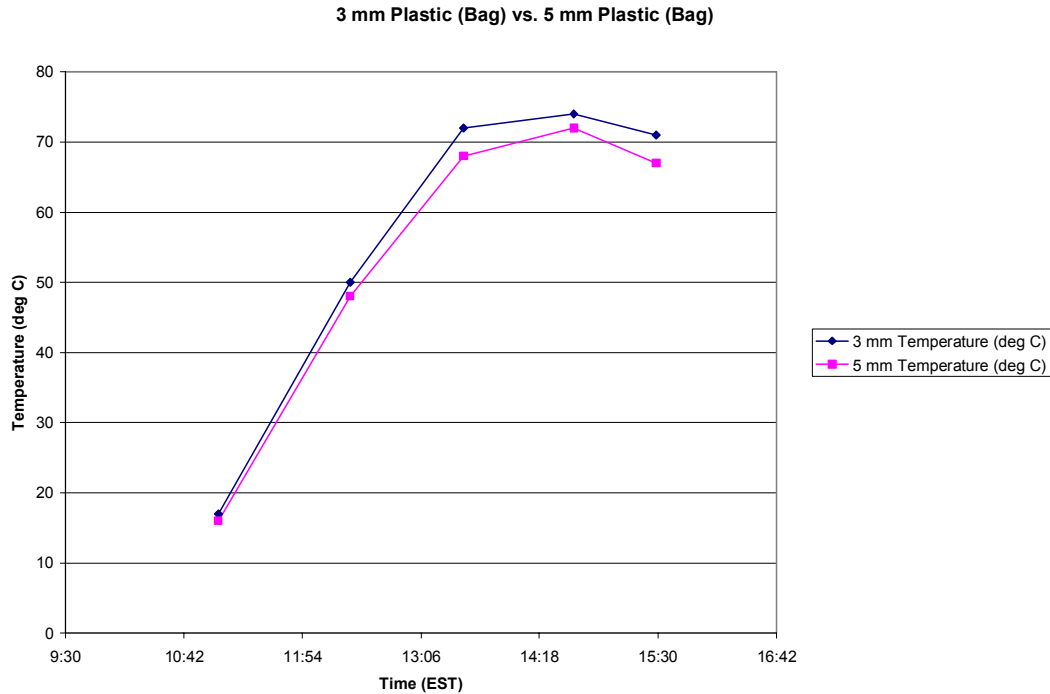


Figure 5: Test 5

The results of this test met our expectations. The thinner prototype outperformed the thicker prototype. The results of all five tests lead us to conclude that the plastic prototype can perform just as well as, if not better than, the cardboard CookIt. An oversized front panel hindered our first prototype, but we were able to correct this with our second prototype.

Bag Durability Testing Procedure

In addition to the solar cooker structure, we decided to expand our analysis and assist Dr. Andreatta in testing bag materials. In order to conduct long term bag material durability testing, we constructed a large reflector out of corrugated plastic and aluminum foil. This reflector is large enough to house two bags containing pots as well as an additional bag. It is simply a large rectangle that is folded in the middle in order to direct more sunlight onto the bags than would be seen normally. The reflector is designed to be placed outdoors for a long period of time in order to observe how well the different bags stand up to constant sunlight.

Bag Durability Testing Results

Unfortunately, the reflector was not constructed until about the eighth week of the quarter. This was due to the fact that other testing procedures took precedent for what we intended to achieve this quarter. Also, we wanted to make sure that we had enough corrugated plastic material for solar heat/tensile testing before committing a large portion of our available material to this reflector. Although it is too early to draw conclusions about the specifics of the durability of the different bags, Dr. Andreatta will continue this testing once the quarter concludes.

Longevity Testing

In order to back-up our claim from last quarter that the corrugated plastic prototypes were water resistant, the prototypes were left set up outdoors in-between testing and exposed to the elements of nature. As expected, the corrugated plastic was not adversely affected by rain or condensation. Over several days of exposure the only negative drawback observed was a slight peeling of the aluminum foil. However, this peeling was only observed in a few places and was small enough to be ignored as a potential design flaw. Were this project ever to be realized on a large-scale, manufacturing methods would be much more precise when attaching the reflective surface to the corrugated plastic.

Material Strength Testing

We used an Instron machine to test material strength in two different cases. Our goal in the first case was to understand the effect of basic folds on the material strength of various thicknesses of corrugated plastic. The goal in our second case was to verify that the chosen prototype material would not demonstrate fatigue failure over the course of the product's

lifetime. We used the same basic testing method in both cases. We used samples that were approximately two by one inches for all material strength testing. Once the samples were prepared, we placed each in the Instron clamps such that the edges of the clamps were close to the portion to be tested, in other words the fold line. We set the Instron to a speed of 25 samples per second in high gear. Labview was used to obtain the applied force, in pounds force, as related to the sample number.

Though the setup was the same in both cases, the sample preparation was vastly different. In the first case, we wanted to generate a comparison between the strengths of corrugated plastic of different thicknesses at a fold line. Thus, in this case, we prepared samples from each of the three material thicknesses including thin (2 mm), mid (3 mm), and thick (5 mm). Since we knew that the orientation of the corrugations would affect the strength, samples were made for each material in the two extreme orientations of the corrugations (parallel and perpendicular) as compared to the fold line. Most importantly, we needed to consider the different potential fold methods. These methods include a plain fold generated using a break press or other method and a partial cut fold in which one plain of the plastic sheet is cut leaving the other plain intact. Thus, samples were generated for each of the three material thicknesses using the two different fold methods in each corrugation orientation.

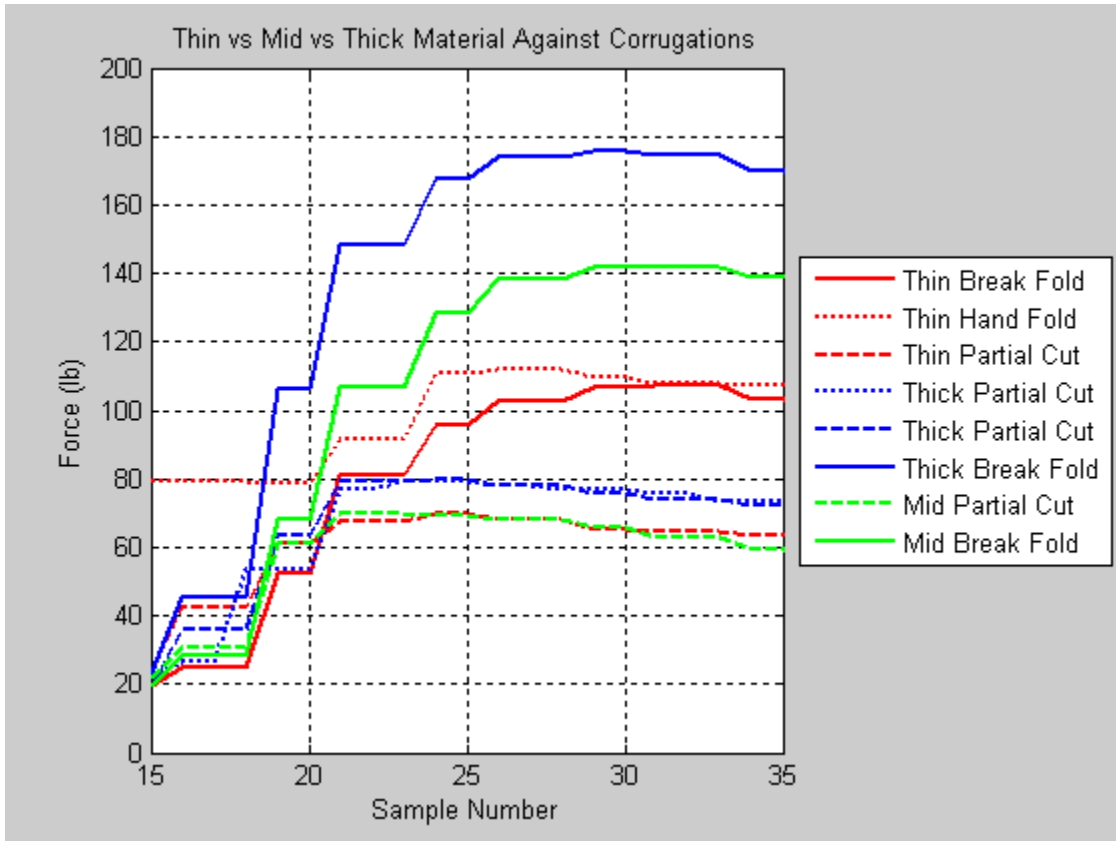


Figure 6: Material and Fold Comparison for Perpendicular Corrugation Orientation

Figure 1 is a comparison between the different folding methods used on each of the three material widths when the corrugations were oriented perpendicular to the fold line. The solid line in each color shows the strength of the material when the sample was folded using the break press. The dashed line in each color shows the strength of the material when the material was partially cut. The dotted line in each color shows the strength of the material when some other fold method was used or when a sample was repeated. The data shows that the partial cut technique resulted in a lower strength than the partial cut method for all three materials, as expected. The data also shows that all three materials performed at approximately the same strength level when the partial cut technique was used. We expected this result as well since all three sheets are made of the same type of plastic. However, the material thickness appears to be

proportionate to the strength when the break press folding technique is used. Thus, the thick material showed the highest results followed by the mid material and then the thin material.

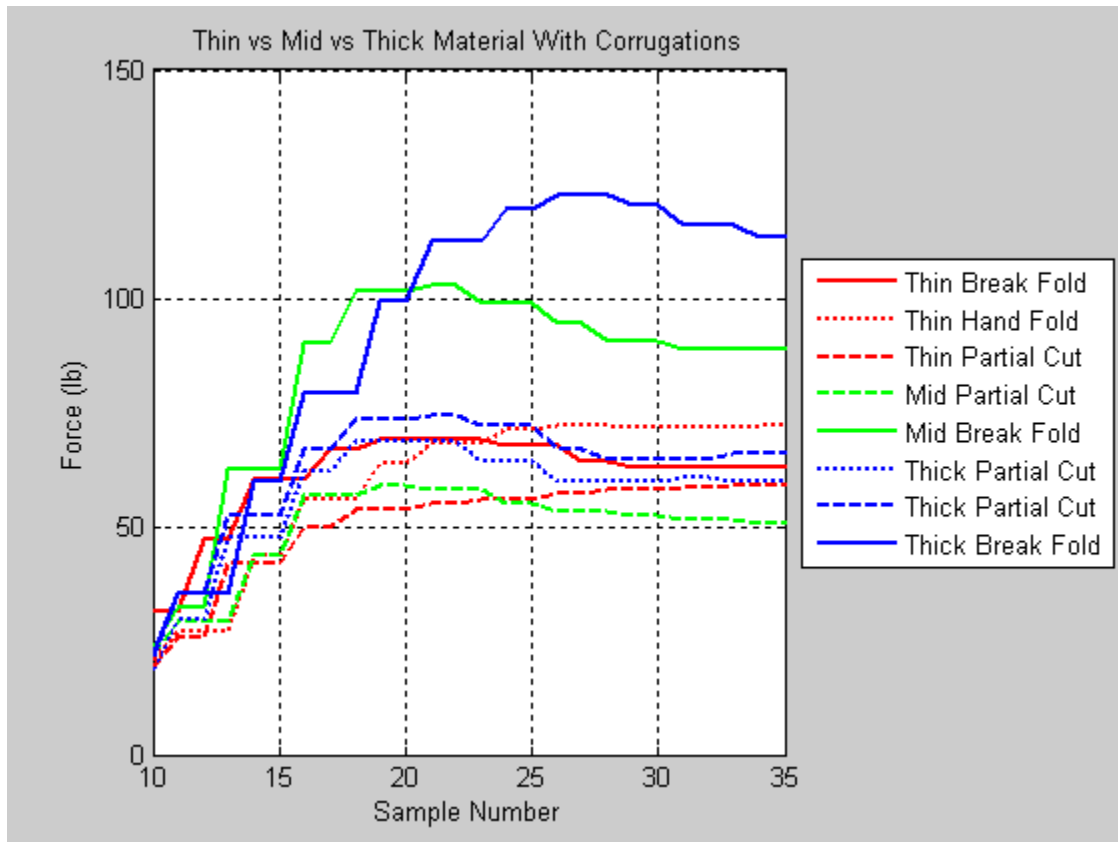


Figure 7: Material and Fold Comparison for Parallel Corrugation Orientation

Figure 2 shows similar results to those of Figure 1 when the fold line is in parallel with the corrugations. The strength for the break press fold technique is again proportionate to the thickness of the material. There were greater discrepancies between the materials and fold methods in this fold direction. This is most likely due to variations in the placement of the clamps on each sample. Though we tried to position the clamps close to the fold line, the corrugations close to the fold line provided weak points other than the fold line. Thus, many of the samples gave way between corrugations at random and not necessarily at the fold line as in the case when the fold line was perpendicular to the corrugations.

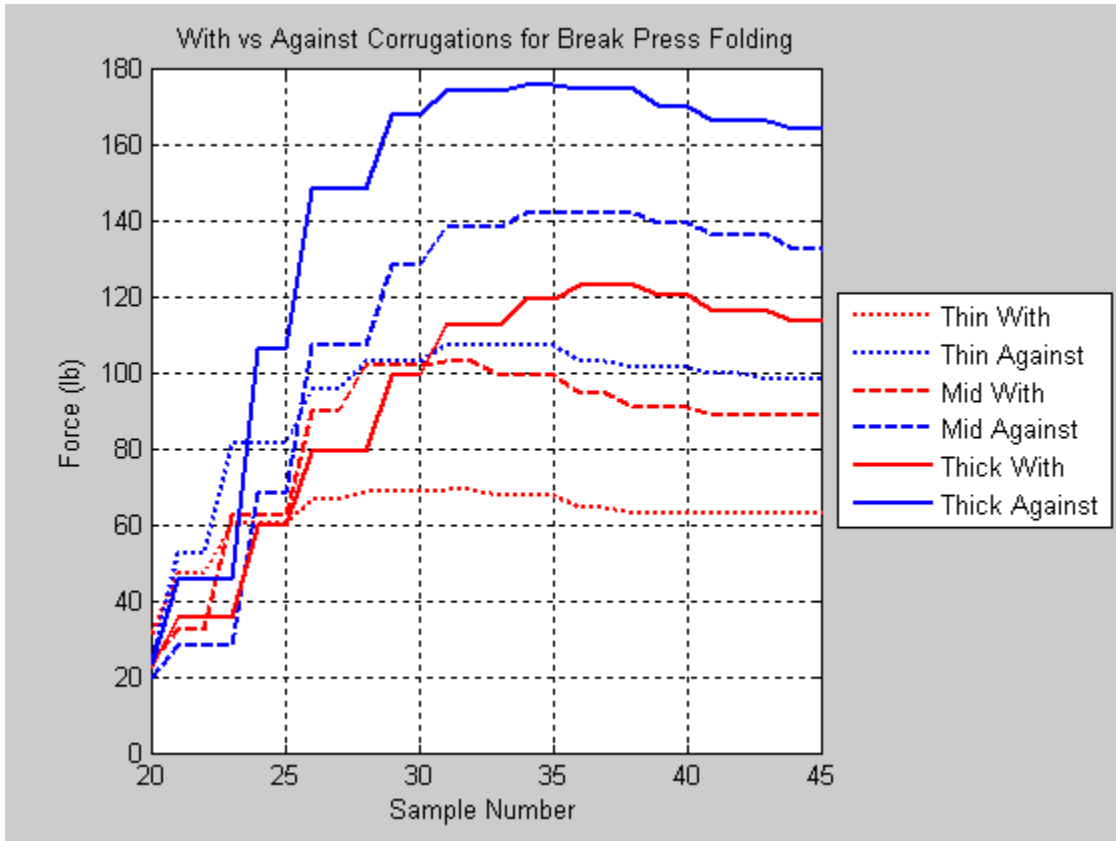


Figure 8: Corrugation Orientation Comparison for All Materials with Break Press Fold

Figure 3 shows a comparison between the fold line directions for the break press folding method used on each material. The red lines denote the parallel direction and the blue lines denote the perpendicular direction. As expected, the corrugations have a strengthening effect on all materials when they are perpendicular to the fold line. The added strength is approximately proportionate to the thickness of the material (in other words to the width of the corrugations). Despite the weakening effect of the parallel corrugation orientation, all three materials demonstrate more than enough strength for the desired application regardless of corrugation orientation.

In the fold fatigue testing, the samples were generated under vastly different considerations. First, we chose to only test the mid thickness (3 mm) material because this was our recommendation for an optimal design material. We also chose to create all the samples

with the same corrugation orientation. The horizontal orientation was selected based on the previous tests that showed this to be the weaker of the two orientations. We created nine samples of approximately the same size. Each was first folded approximately in the center in the same orientation as the corrugations using the break press. Four samples were folded 250 times and another four samples were folded 500 times. The ninth sample was folded 1000 times. We chose to fold 500 times by conservatively estimating the number of times the unit would be folded over its lifetime. This estimate was based on our background knowledge of the previous products use as well as the expected climate and seasonal weather patterns of the target market. We chose to test a sample folded 1000 times in the event that our estimates of the products life should be wrong. We felt that if this sample showed a rapid decrease in strength we would need to verify our estimations and possibly complete further testing at higher fold numbers. We also tested at 250 folds to illustrate a full array of data for comparison should any important trends arise.

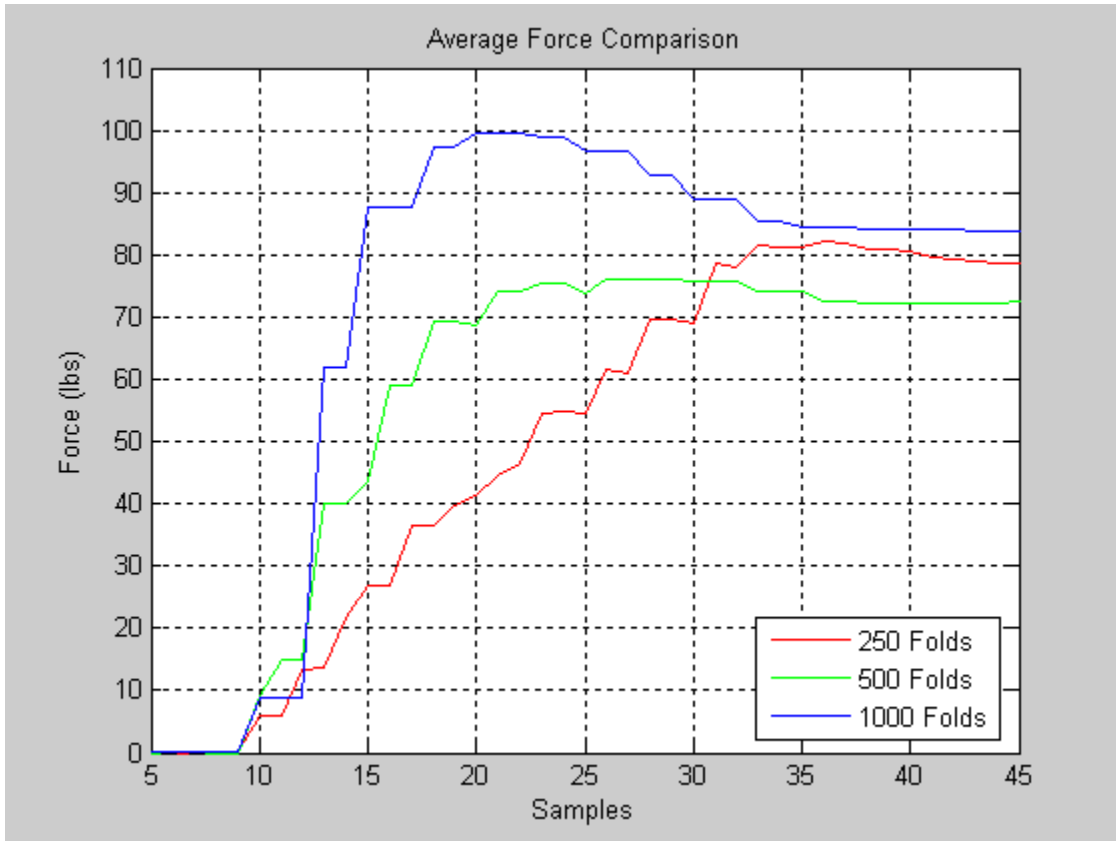


Figure 9: Average Force Comparison for Varying Fold Numbers

Figure 4 illustrates the averaged results of the fold fatigue testing. The red line represents 250 folds, the green line 500 folds, and the blue line 1000 folds. All three fold sample numbers resulted in acceptable strength values. No reduction in strength was found in the 1000 fold sample, which actually performed at a higher level than the other two sample sets. While this increased performance could be a fluke, we felt it obvious that the 1000 folds had not in any way weakened the material. Thus, we concluded that the material we selected for the design is resilient and fatiguing at fold lines over prolonged product use will not be an issue.

Material Acquisition

One of the most important responsibilities this quarter was to test several different thicknesses of corrugated plastic to determine which performed optimally. The three different thickness samples tested were the 2mm, 3mm, and 5mm. Having already been provided the 5 mm thickness (last quarter's prototype) by Dr. Dale Andreatta, the 2 other thicknesses had to be acquired in order to do comparative reflective and strength testing.

After researching and asking Dr. Andreatta if he knew of a good supplier, we encountered a company by the name of Amatech-Polycel located locally in Columbus, Ohio. The local company was a reliable source and had the two thicknesses we intended to test available. We wanted to obtain plastic sheets that were white in color, however, black was the only color in which they had in stock. The white sheets could be obtained by ordering from the Erie, Pennsylvania site, however, this was not necessary for our prototype. After contacting Amatech-Polycel for the plastic, we were fortunate enough to be given the materials free of charge. This made for low budget prototype testing this quarter.

Another sheet of black 5mm thickness material was obtained from another supplier in Columbus called American Plastic Distributors. This material was taken from their scrap inventory and was purchased for less than a dollar. The small scrap piece of plastic was used to do strength testing after the original material supplied by Dr. Andreatta was depleted. We felt that the 5mm plastics from Dr. Andreatta and from American Plastic Distributors were very comparable to each other, thus the strength would not vary much.

Manufacturing Considerations

One of the major manufacturing considerations, aside from the process of cutting the plastic to shape, was the folding process. Several methods of folding the corrugated plastic were

looked at throughout this project to determine which would be the most feasible method. As explained earlier, the straight fold method allowed the prototype to be fold exactly like the CookIt. This folding technique could be accomplished in the manufacturing process with two possible solutions.

Researching online led us to a patent for a “method and apparatus for heavy corrugated plastic construction” (patent # 6056840) designated to a company called Mills Industries Inc. from New Hampshire. The process involves heating a metal blade, which is then pressed into the plastic. This process creates fold-lines with adherable sides that can be used to hold the corners of a box shaped container. A cooling process of the plastic would allow this process to be useful in creating a panel cooker that we need. Once cooled, the surfaces would not be permanently attached to one another, thus allowing them to be folded together.

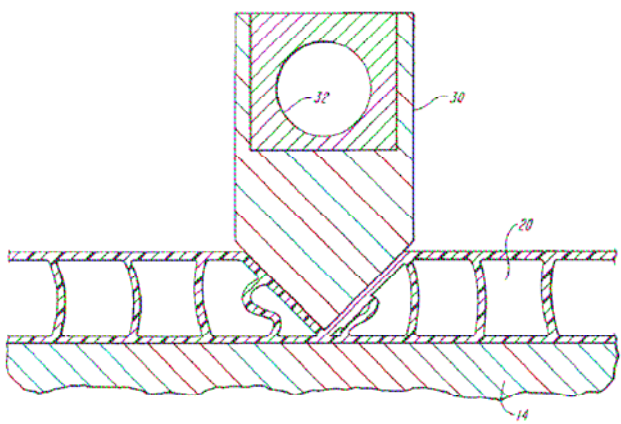


FIG. 2

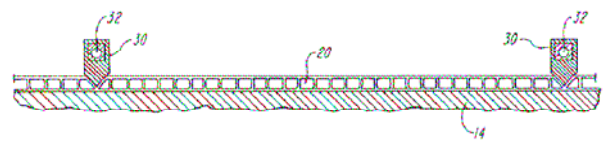


FIG. 3

Figure 10: A drawing that was submitted in the patent from Mills Industries [1]

In our discussions with Amatech-Polycel we learned about a process they use to fold their products into shape utilizing a clipper-die press. The clipper-die press used by Amatech-Polycel and the process that Mills Industries used is very similar.

Material Costs Analysis

Although the materials obtained from Amatech-Polycel were free of charge, we were able to receive some price quotes on the material. We found the 3 mm material to be priced at \$0.21/ft². This price was very similar to that of the price quote that Dr. Andreatta heard through word of mouth. Another material we were looking at was called Econolite®. This material already has an aluminum surface baked into the side of the corrugated plastic with a lamination process. This material would be easier to implement and would optimize our prototype. However, in light of cutting costs and providing a relatively inexpensive product, this material did not meet the standards we were looking for. Quoted at \$2.89/ft², this material was much more expensive than normal corrugated plastic and would be too expensive to use for our prototype. We concluded that the technology to further optimize our product is available, but due to its extreme costs it is currently not feasible.

Future Improvements

Based on testing results from this quarter further optimization of the product could be done. The aluminum foil did not hold up very well in the durability testing. A better application of the aluminum covering or another aluminizing process should be looked into. We also researched possible proprietary processes that could produce the material we were looking for.

After researching we found a material now as Econolite® distributed by Meyers Plastics in Indianapolis, Indiana that was available in a 6 mm thickness that was white in color with a painted on aluminum surface on one side. After contacting Meyers Plastics, we were able to learn a small bit about the manufacturing process and received some price quotes. Econolite® is created by mixing an adhesive additive into an aluminum paint that is baked onto a sheet of corrugated plastic in a lamination process that seals and protects the surface. It was quoted at \$2.89/ft², a price well beyond a feasible material for this third world project.



Figure 11: The Econolite® product photo [2]

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<http://www.meyerplastics.com/signandgraphics/corrugated_plastic_center_materi.htm>

Appendix

Gantt Chart:

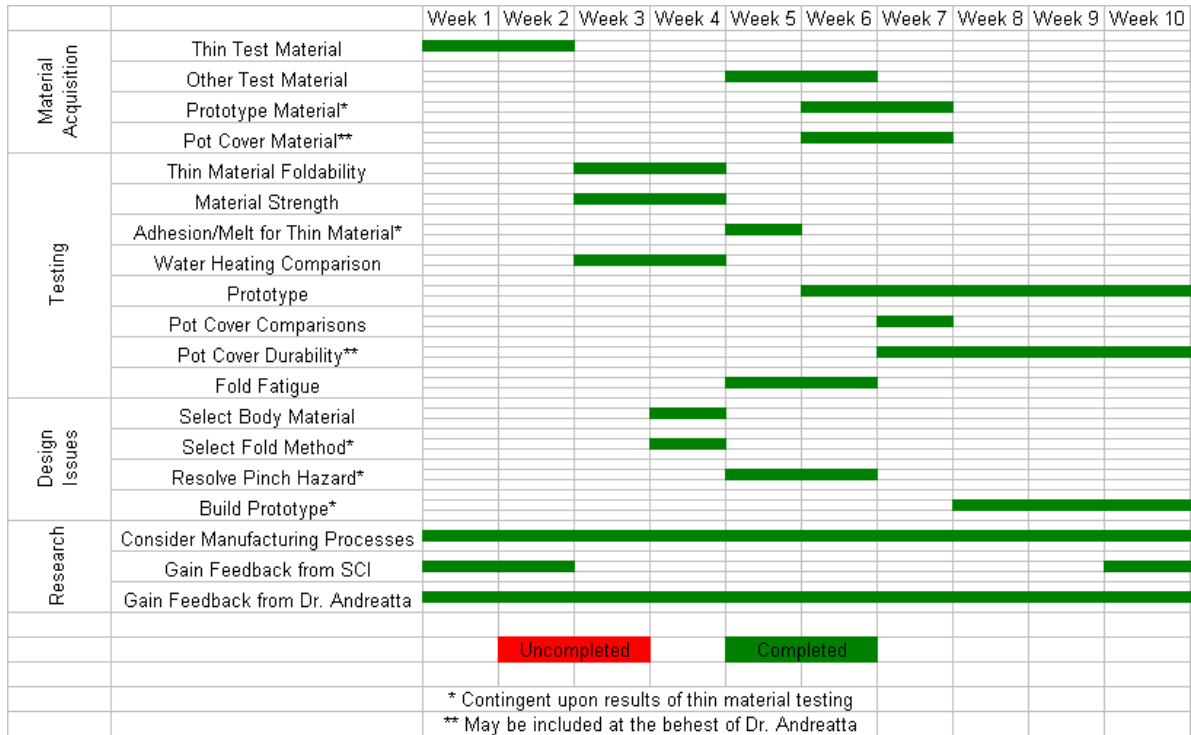


Figure 12: SP07 Gantt Chart