# Low Temperature Household Energy with Solar

**Dale Andreatta, Ph.D., P.E.**

**August 30, 2018**

**dandreatta@sealimited.com**

## Introduction

In the developing world household energy includes stoves and also includes tasks that require a considerable amount of energy, but at temperatures well below cooking temperatures. Many of these low temperature functions could be done with solar energy. Ideally, a general purpose versatile solar heater could be built that could perform a lot of tasks simultaneously, with significant reduction in labor. The users would determine which tasks they needed.

There is need for a device that can:

1. Dry grain, primarily corn
2. Heat water for washing (target temperature 50°C)
3. Preheat a pot of water that would then be used for cooking (target temperature 70°C)
4. Pasteurize drinking water (target temperature 60°C)
5. Dry wood, to be used later for cooking fires
6. And finally, if you can heat enough water and have an easy way of getting it into the home, it can form an effective space heater for chilly nights (target temperature 50°C).

The device that was developed is a very inexpensive way to accomplish all the above tasks. It was reported to me, and observed by me in my limited field experience, that 5-gallon (20 liter) buckets are readily available in most parts of the world, bricks are readily available (definitely so where I have been in Malawi) and small bottles are readily available. The device that was developed was largely based on these.

The author is located in Ohio in eastern North America at 40.1° N latitude, in a fairly humid rainy summer climate. Near the summer solstice the author's location should give results similar to a tropical sun any time of the year due to similar solar angles. In the author's location most afternoons are partly to mostly cloudy, with a high probability of clear weather in the morning and evening. There are occasionally days near the summer solstice when it is clear all day. There are days when it is mostly cloudy, and some results will be given for all types of days.

Tests were performed in 2018 from around the solstice to mid-August, at which point it was believed the sun was too low in the sky to simulate a topical sun. On some days side by side heaters were used, identical except for one design variable. The design was modified along the way, usually by making simplifications, and in most cases the simpler design worked as well or better than the more complex design. This report presents the final design, but gives experimental results from various designs, with the idea that the final design would give results at least as good.

## Background of Space Heating

Large portions of Africa, and other places around the world, are far above sea level and the nights are chilly. If one needed space heating, one could use two solar heaters of the type that will be described side by side, each with 4 buckets. If each bucket contained 18 liters and was heated to 50°C, then in cooling to 20°C a total of 18 MJ of heat is released, the equivalent of 5 kW-hr of electricity, or 390 g of LPG, or 1.1 kg of wood, or 600 g of charcoal. If the house is poorly sealed, the large surface area of the buckets will transfer heat to the occupants partly by radiation, which is still effective in a poorly sealed building. Finally, one could use the buckets like hot water bottles, with each occupant of the house having their own bucket and by keeping close to them while sleeping, could stay warm. In the last case, you would probably cover the bucket with a blanket to keep it from cooling to 20°.

## Background of Pasteurization

Pasteurization is the heating of a food or beverage, in this case water, to a temperature sufficient to kill all pathogens. The temperature varies with the organism and varies slightly with the liquid, but microbiologists have determined that Hepatitis A is the most heat resistant pathogen, and is killed in water by 65°C in a few minutes, or 60°C in about 30 minutes. Since with solar heat the water heats up and cools down very slowly, 60° is the target temperature in this study.

It is not necessary to boil the water as many people believe. The reason boiling is used is that it's difficult to tell when water reaches the pasteurization temperature. Over the years, several pasteurization indicators (usually called WAPIs, for Water Pasteurization Indicator) have been developed. These typically have a sealed tube with a small amount of wax that melts at the pasteurization temperature, and then some means for making sure the wax starts out solid in the high end of the tube. If the wax is found later in the low end of the tube as either solid or liquid, then the correct temperature was reached. One type of indicator with a glass tube is shown in Fig. 9 of this report. Typically, the wax is a type that melts at 65°C or a little more, so the WAPI is somewhat extra-safe, and may give a false negative. This is especially true as most pathogens are killed by lower temperatures than Hepatitis A.

## The Design

The basic unit is shown in Figures 1 through 7. This unit is about 1.2 meters in the north-south direction and 2.2 meters in the east-west direction, though different dimensions could be used. These dimensions seemed to be a good balance between having enough area to pull in a lot of heat, and still keep the plastic sheets manageably small. One could build multiple collectors if one wanted a lot of buckets for space heating or other purposes. One can use any number of buckets up to about 5 in this size of collector, though having more buckets means a lower final temperature. Preliminary analysis said it was slightly better to orient the long axis east-west, though this is not an important factor and was not confirmed.

There is a layer of straw (many other things would work as well) about 5 cm thick, a black plastic layer, then the heating space. Figure 3 shows two buckets of water in the heating space as well as large and small wood to be dried. Also seen is the arrangement of bricks used to support the buckets. The bricks are arranged with the medium dimension vertical. Orienting the bricks with the tall dimension vertical did not help. It is believed to be important to allow some heat to get to the bottom of the bucket through radiation and convection, therefore the buckets can't just rest on the plastic. Under the black plastic are more bricks for stability.

*Figure 1: The straw used as the bottom insulation. It is about 5 cm thick.*

*Figure 2: The straw covered by black plastic.*

*Figure 3: An arrangement of two buckets, large wood, and small wood. Note the bricks supporting the buckets.*

*Figure 4: An arrangement of two buckets and three different sizes of water bottles to be used for pasteurization.*

*Figure 5: An arrangement showing three buckets and about 3.3 kg of corn to be dried. The layer of corn is just under 1 cm thick.*

*Figure 6: A cooking pot with 5 liters of water. The clear top gives the best performance, but an opaque top works almost as well.*

Three different sizes of pasteurization bottles are shown in Fig. 4.  Having dark bottles is helpful.  The top layer is a single sheet of clear to translucent plastic (either one seems to work about as well).  Figure 7 shows one unit with clear plastic and the other with translucent.

The best variation is with no lid on the bucket and the clear plastic top sheet draped across the top of the bucket.  This allows direct solar radiation into the water, which is efficiently absorbed.  Tests with lids on the buckets were somewhat less positive.  Test with lids on the buckets and then some sort of spacer to create an air space over the lid and below the plastic sheet were somewhat less positive.  In this respect, the simplest option worked the best.  The buckets need to be a dark color to get full heat.  White buckets heated, but not as well as dark buckets.

*Figure 7:  The test units fully set up.  The near unit with the water bottles has a clear cover and the far unit with the wood to be dried has a translucent cover.  Both seem to perform about equally well.  The clear plastic is draped over the open tops of the buckets to allow sunlight to hit the inside of the bucket.  There are no lids on the buckets.*

The straw layer was quite wet by the end of the season, but it still seemed to perform well.  On some tests direct measurements were taken of the black plastic, and the plastic got very hot even with the straw wet.  Some of this water probably came from ground moisture, as the rain soaked into the ground poorly in the high clay soil, and some of the water came from condensation that worked down through the black plastic.  The black plastic had a number of small slits in it to allow water to drain through if necessary.

In the humid summer weather the clear layer was full of condensation each morning both inside and outside, and the black plastic also had some condensation.  The device seemed to work well even with the condensation, and by afternoon the condensation was gone.

The bottom edge of the clear plastic in Fig. 7 does not form a perfect seal. The device still works, as long as there are no large gaps. Warm air rises, and there is limited tendency for air to be exchanged between the inside and outside of the unit, unless there are large gaps and it is windy.

The plastic top sheds rain well. In the rainy climate where the tests were done the top was closed at night without the buckets inside. If it rained, the cover was rolled back before the next test to drain the water off the plastic sheet. In a dry climate it might be better to leave the unit open at night.

In the two months of testing the plastic showed no degradation, though it would eventually weaken under the effects of the sun. Previous testing by the author suggests that 3 months of life could be expected with non-UV stabilized plastic, much longer with UV stabilized plastic.

## Results

Looking first at the water heating applications, Fig. 8 shows the temperature curves for 3 different sizes of water vessels. The buckets hold about 17.1 liters of water and would be used for washing or space heating. The design of the collector was not fully optimized at this point. The bucket data comes from August 19, a mostly sunny day and there were two buckets in the collector as well as smaller items. The temperature goal of 50°C was reached, starting from about 20°. Various discontinuities in temperature for all the vessels occur when the thermocouples were inserted or taken out of the water.

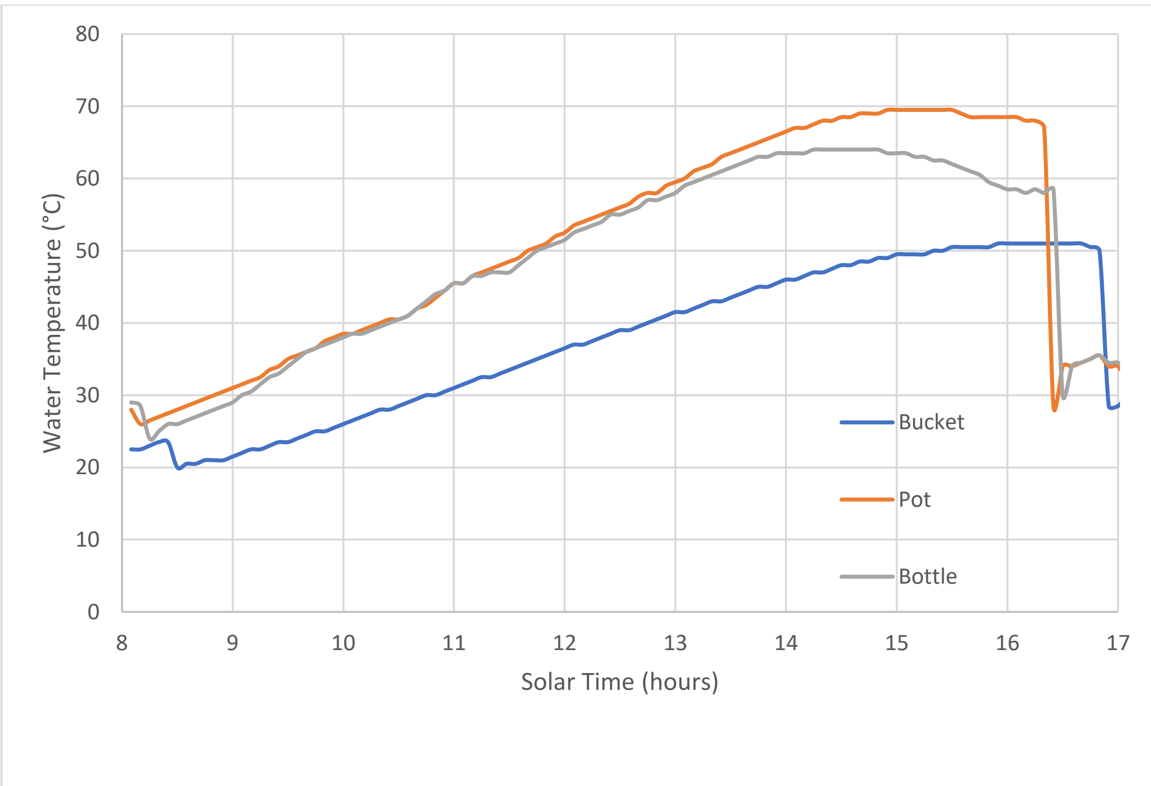


*Figure 8: Water heating curves for 3 sizes of water vessels, all on mostly sunny days.*

For the bottle and the pot the data comes from August 4, also a mostly sunny day. The goal of achieving pasteurization (about 60°C for about 30 minutes) was achieved for the bottle, which in this case was a brown beer bottle holding about 633 g of water. For the real case you would use a rack of such bottles, and since the bottles are small compared to the collector, they do not pull enough heat from the rest of the system to affect the performance of the rest of the system.

Bottles of all sizes up to 2-liter seem to reach about the same peak temperature, in the mid-60's, assuming that it is sunny. Larger bottles heat up more slowly than small bottles, and if it is partly cloudy the larger bottles are more likely to run out of daylight before achieving pasteurization.

The pot was a black steel pot with a black steel lid, holding about 5 liters of water. It almost achieved its goal temperature of 70°C, falling short by half a degree. A later side by side test of a pot with a clear lid (a sheet of plastic tied tightly could also be used) and a pot with an opaque lid showed about a 4° improvement with the clear lid, so the pot test design was not fully optimized by August 4, the day this data was taken. Some tests were done with a pot with a reflector inside the solar collector, but these did not perform significantly better or worse that the simple black pot.

On all test days the test started about 4 hours before solar noon (08:00) and ended about 4 hours after solar noon (16:00). The logging sometimes continued afterwards, but the "official" test ended at 16:00. Local solar noon was actually at about 13:25, Eastern Daylight Savings Time.

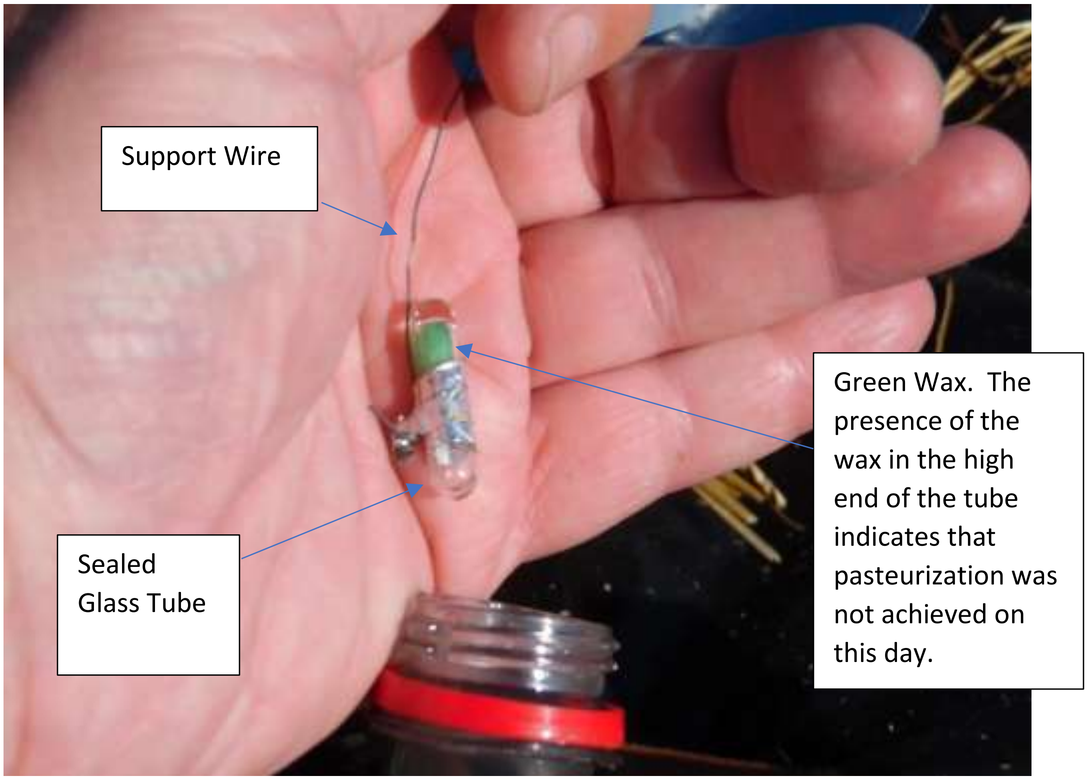


*Figure 9: The Water Pasteurization Indicator (WAPI) being pulled out of a bottle. On this day, the indicator was negative.*

Figure 9 shows the WAPI being taken out of a bottle. On this day the wax did not melt, giving a negative reading. As previously stated, the WAPI is somewhat over-safe, and it's likely that most or all pathogens would be killed on most days. The WAPI is reusable immediately, and if necessary the tube can be inverted by bending the support wire. The wax must start out in the high end of the tube at the start of the heating.

The effects of weather were considered. The results for heating are mostly a function of the amount of sun, and to a lesser extent the ambient temperature. In other words a sunny cool day is better than a cloudy hot day. Figure 10 below shows the water temperatures in a bucket on mostly sunny, partly cloudy, and mostly cloudy days.

The mostly cloudy day was July 4, where the previous overnight temperature was high and the starting temperature was high. On this day there were four buckets in the collector, while on the other days there were only two. Some heating was achieved, but the goal of 50°C was not reached. Had there been only two buckets, the final temperature would have been at least a few degrees higher. The mostly sunny day was July 12. The partly cloudy day was August 14, and it was sunny in the morning, then cloudier as the day went on. The partly cloudy temperature exceeds the sunny day temperature until the effects of gathering clouds became greater in the late afternoon.

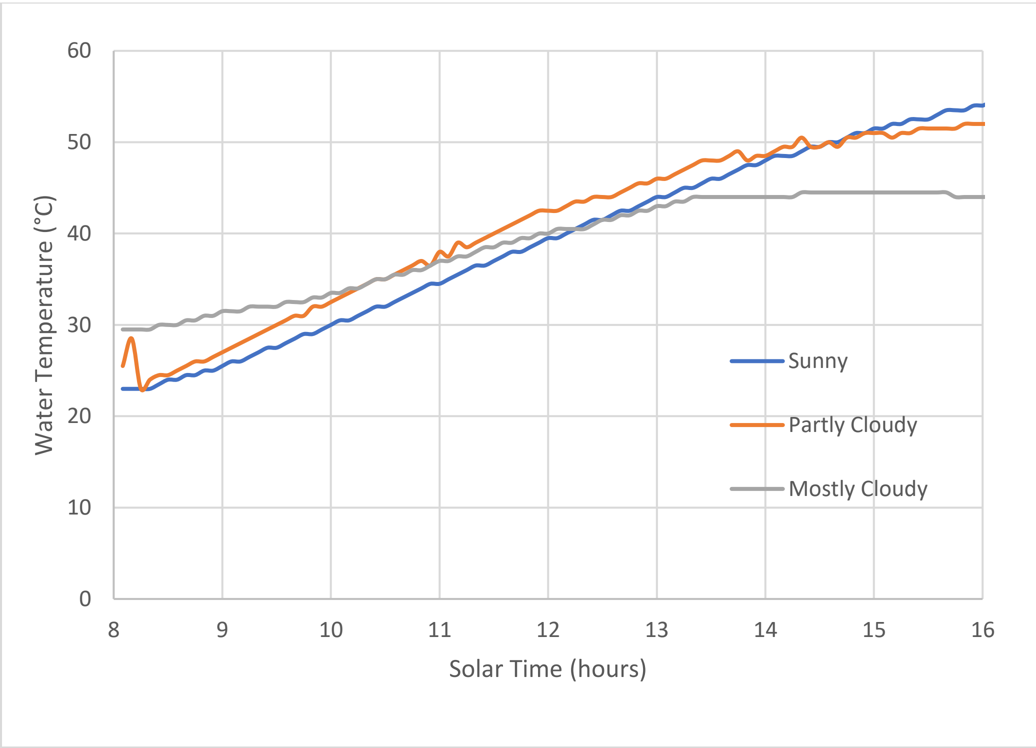


*Figure 10: Bucket temperatures on 3 different days with 3 different sets of weather conditions. See text for details.*

For the drying applications, Fig. 11 shows data from drying tests on 3 items of common interest. One is corn, which was purchased as “squirrel feed” locally in the form of dry field corn. It was rewetted overnight to get the original high water content, then dried for 3 days. It’s possible the corn was made too wet at the start of the test and in a real situation where the corn is fresh from the field the original moisture content would be more like that after one day of drying. The corn drying arrangement was shown in Fig. 5. The corn is on a separate black plastic sheet to make it easy to gather up.

The 3.3 kg of corn covered an area of about 1/3 square meter and had a depth of about 1 cm. The temperature at the bottom of the corn layer was measured on each of the 3 drying days, and on each day it was over 50°C, with over 60° being achieved on the second and third days. On each day the temperature was enough to kill insects and insect eggs.

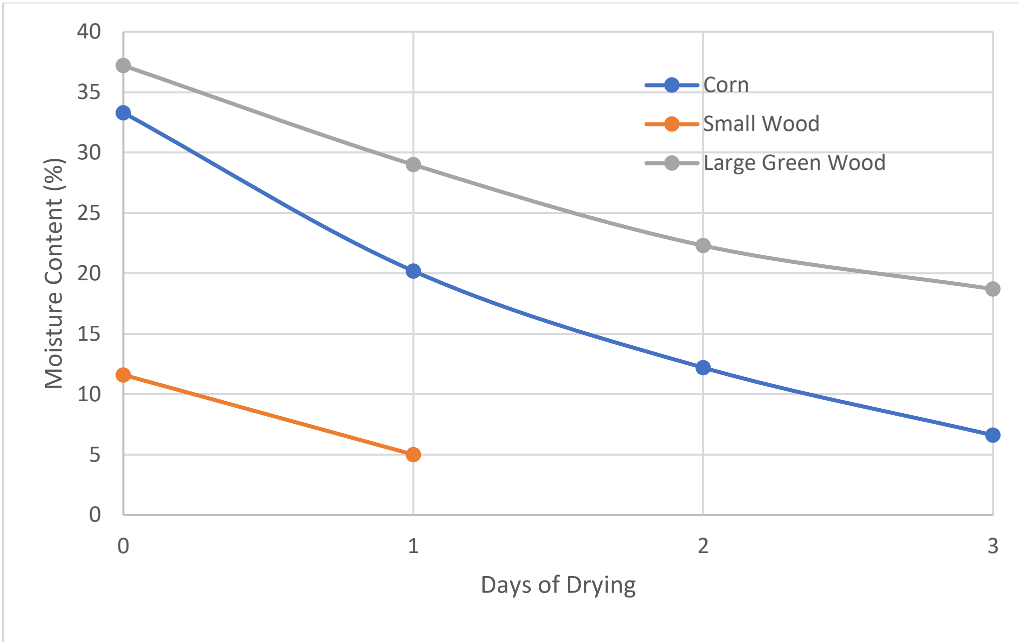


*Figure 11:  The results of drying tests with 3 different items.*

The large wood and small wood were shown in Fig. 3.  The small wood had been off the tree for a long time and was already largely dried at the start of the test.  The large wood was originally about 7 cm in diameter, but split in half.  This is similar to wood seen in Malawi.  The first day of drying was the morning after it was cut off a tree, therefore its original moisture content was very high.  After 3 days the moisture content was much lower.

Obviously dry wood burns better than wet wood, giving more energy, usually burning cleaner, and burning more steadily with less fire tending necessary.  Characteristics of a good stove are that they are clean, efficient, and easy to use.  To some extent these features can be provided by drying the wood.  As is sometimes pointed out, a good stove is not just about the stove, it's the complex interaction between fuel, stove, and user.

In all cases the moisture content is on a wet basis, and was determined by fully drying the sample in an oven after the solar tests so that the dry weight could be measured.  In all cases, the amount of energy absorbed by the evaporation is small compared to the overall collector, therefore the presence of a small amount of wood or corn would not have much affect on the overall solar heater, and buckets, pots, or bottles of water could also be heated at the same time.  There was never condensation inside the top clear layer of plastic during the day, therefore there was enough air exchange to get the moisture out of the collector.

## Theory and Technical Details

This section contains some background science and technical details.  Before beginning with tests, some numerical modeling was done that suggested that the basic idea would work, that an east-west orientation of the long axis was better than a north-south orientation, and the modeling suggested some optimum dimensions which were used as a starting point for the experiments.

The energy transfer routes in this type of collector are perhaps not obvious. The device is an "energy concentrator" that works not by concentrating the sun's rays, but by collecting as much heat as possible and then getting some of it into the target. The author is aware of no other solar collector that works according to these principles. The collector is designed for minimum cost per MJ. The efficiency has never been calculated but is not high. The maximum possible temperatures for this type of collector are not high, but for this application the temperatures are adequate. Again, the goal is to get as much energy as possible per unit cost.

Some heat is lost into the ground through the straw insulation, but the bulk of the heat is lost through the glazing to the atmosphere. Radiation is an important mode of heat transfer to and from the glazing. In the early part of the day when the buckets are cool, the glazing is warmer than the buckets and transfers heat to the buckets via radiation.

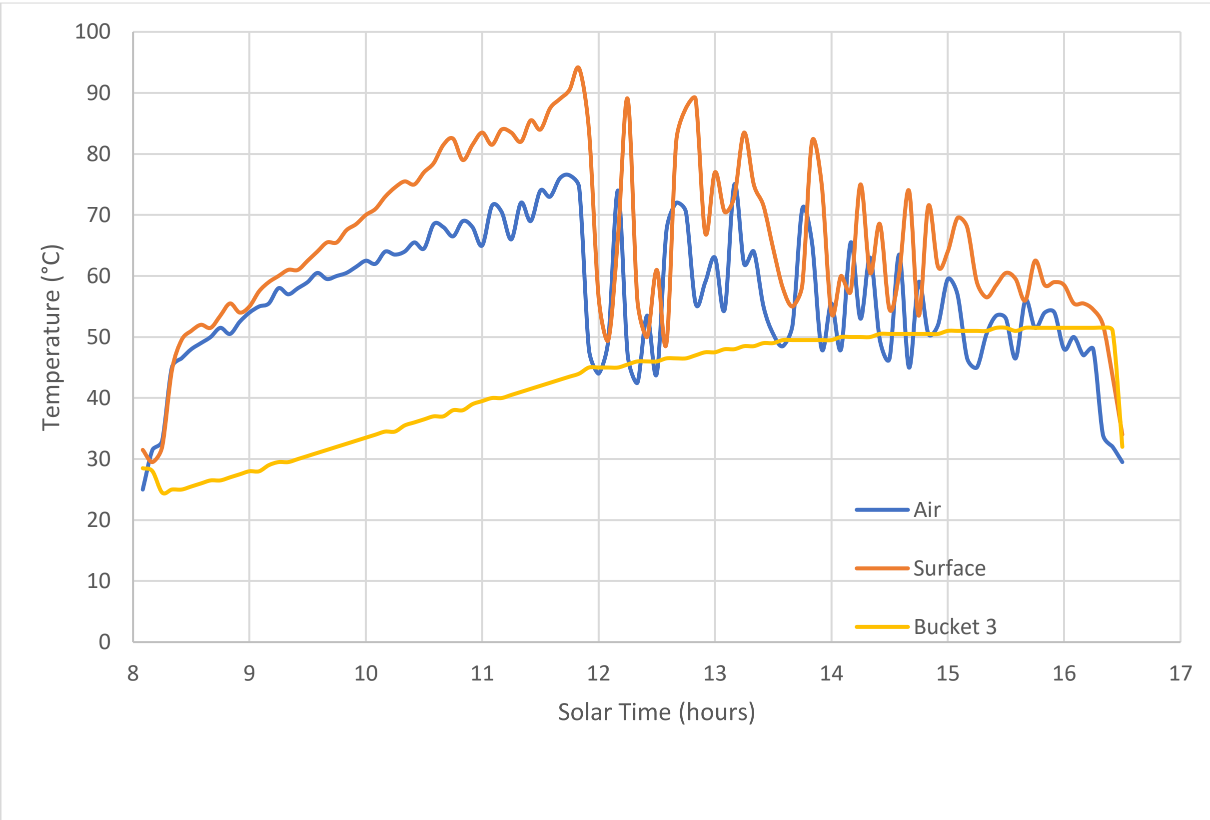


*Figure 12: A comparison of the temperatures on the black plastic surface, the air above that surface, and the bucket water temperatures on a single partly cloudy day, August 14. See text for details.*

The figure above shows 3 temperature traces from the same day. The thermocouple was inserted into the water and the collector was covered about 10 minutes after the start of logging, which was about 4 hours before solar noon. The surface temperature of the black plastic and the air temperature rise quickly and trend together very consistently, with the surface generally hotter than the air. It was mostly sunny until solar noon, a pattern that occurred on many days. The temperature rise rate of the water sharply decreased at that time, but the temperature continued to increase and the temperature at the end of the test at 4 hours after solar noon was over 50°C. The peak temperatures of both air and surface are highest at solar noon, when the sun is closest to perpendicular to the surface.

It can be seen that the peaks of the surface temperature follow a roughly half-sine wave pattern, which would be expected. Breaks in the clouds in the afternoon lead to high surface temperatures momentarily. Clouds can actually increase solar collection momentarily. The ideal condition would be to have the sky filled with thin clouds that scatter light, except for a break in the clouds directly in front of the sun. With this condition the direct rays from the sun come through and there is additional scattering from the clouds. The worst condition is the opposite, a small thick cloud right in front of the sun with blue sky everywhere else that scatters little. The scattering from the clouds is one reason why the unit performs almost as well on a partly cloudy day as on a sunny day, as seen in Fig. 10.

The black plastic layer gets very warm and radiates heat to the buckets or other things in the collector. The plastic is frequently over 80°, leaving a temperature difference of 30° or more between the plastic and the bucket.

The collector also heats the air inside it which in turn heats the buckets and other things inside the collector by convection. Figure 12 shows a significant temperature difference between the air and the buckets. The numerical models suggests that about equal amounts of heat are transferred by convection and by radiation, with a third equal amount of heat striking the buckets from direct sunlight.

The heat loss from bucket to ambient can be studied. On several days the tests were run into the late evening while the bucket temperature was monitored. One such graph is shown below, showing the temperatures through the day for a full bucket and a bucket that was ¾ full. The non-full bucket reached its peak temperature sooner, reached a somewhat higher peak temperature, but the full bucket retained its heat better due to the higher mass. This test day, June 30, was unusually hot with about 34°C peak temperature. One thing was different between this day and a typical tropical day, in the higher latitudes the days are longer, thus, at 4 or more hours after solar noon at the test site in Ohio the collector is still getting some solar energy, while in a tropical location the sun would be much lower in the sky at this time. A more direct comparison would be to look at the temperatures 4 hours after solar noon, the time at which the sun would be about 30° above the horizon in the tropics. At this time the ¾ bucket is near its peak while the full bucket is about 5° cooler, but still rising in the high latitude location.

Looking at the temperature drop rate during the last hour of the test when the sun was low in the sky, the full bucket temperature dropped about 3.5°C, suggesting a heat loss of about 70 W, and with an approximate ambient temperature of 29°C, the heat loss coefficient is about 2.7 W/°C. This will depend somewhat on the number of other buckets in the collector.

During this same final hour the air temperature in the collector dropped to nearly the ambient temperature, suggesting that there was no solar heating (to be expected during the late evening hours) and that there was no stored heat from the ground coming up through the insulation.

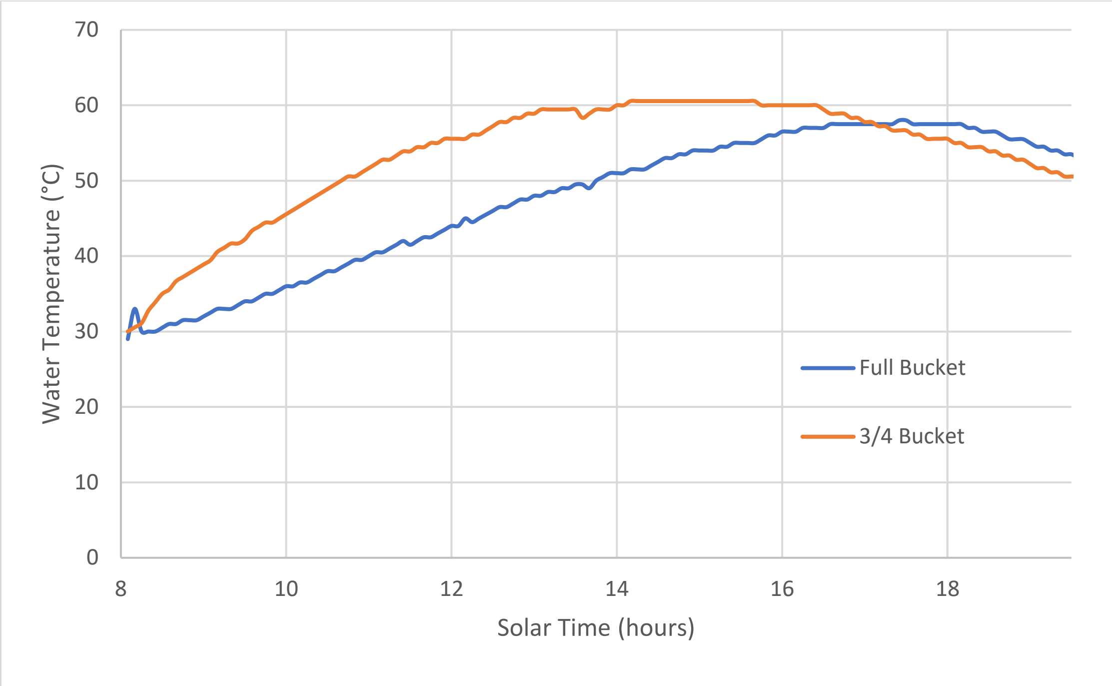


*Figure 13: Temperature graphs for June 30, 2018. On this day there were 2 buckets in the collector, one full, the other ¾ full. The weather was hot and sunny all day. This was not the final optimized design, but was a preliminary design that did not perform quite as well as the final design.*

## Variations

As previously noted, non-full buckets got somewhat hotter and got hot quicker than full buckets. Using non-full buckets is an option, dictated by the user's needs, how much hot water they need, when they want the hot water, and also by how heavy a bucket they want to carry. Of course, if the water is too hot, it can always be diluted with cooler water.

Tests were tried without the black plastic sheet on top of the straw, using only the straw as both insulation and solar absorber. The results, based on a limited number of tests, were almost as good as with the plastic sheet. This seems to be a viable option and will be studied further during the next solar season. The viability of this option may depend on ground moisture, with the rainy weather and poorly draining soil of Ohio being a likely worst case.

A month or so after the summer solstice the sun at its peak was farther to the south than near the solstice. Some limited tests were done with the north side of the black sheet tilted up. This is partly to be more perpendicular to the sun, and partly to increase the radiation from the plastic sheet to the buckets (increased view factor between the plastic sheet and the north sides of the buckets). This made little difference and increased the complexity. This might be a more viable option for systems not too close to the equator during the months near the local winter solstice.

## Companion Video

A short video showing the device, its functions, and the process of applying the plastic covers and using the WAPI is available on youtube. The URL is youtu.be/PlXmttxNeEs (the letter between P and X is a lower case ell).

## Future Work

In the summer of 2019 more rigorous tests will be done under better-controlled conditions. The tests will refine variations in the current best design, now that the best design is generally known. Additional simplifications will be tried, including a more thorough test of collectors with and without the black plastic sheet. Tests with varying numbers of buckets and with varying levels of bucket fullness will be conducted. Tests with a very large pot will be conducted. More tests of collectors with tilted sides will be conducted.

Other applications may be explored including the use of heat to kill insects and insect eggs in clothing.

## Acknowledgements

The author thanks his company, SEA, Ltd, for allowing time, space, and supplies for this project. In particular, the use of temperature loggers purchased by SEA was critical to the success of this project.