Solar Thermal Energy for the Village

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Introduction

At the 2013 ETHOS Conference we were challenged to start thinking about village energy, not just cookstoves. Since I know something about solar thermal energy, this got me to thinking about putting together what I've learned in the last 20 years, along with the recent experiments, into a single document. Here, I will described 3 uses for low temperature (below boiling) solar-heated water, and 3 simple devices for producing that hot water. These methods work best, of course, in hot sunny climates, but they also work well in sunny cool climates, and will provide some benefits in partly cloudy climates. Since most parts of the developing world are near the equator and at low altitude, much of the world can use these techniques. On cloudy days, one might need to revert back to fuel heated water, so this not an everyday solution, but a considerable amount of energy can still be saved.

In Johnson and Bryden (2012) it is estimated that in a particular village in Mali, 22% of the domestic wood consumption went for water heating exclusive of cooking, while another 52% went for cooking. In a sunny climate the methods presented here would provide most of the energy required for water heating exclusive of cooking, and a substantial fraction of the energy needs for cooking.

Three Uses for Hot Water

Three places where hot water can be used, even if it is well below the boiling point, are

1. Wash water, typically at about 45-50°C
2. Pre-heated water for cooking, typically about 70°C
3. Pasteurized water for drinking, typically about 65°C.

More will be said about each of these in turn.

Wash Water

Wash water can be used for washing dishes, clothes, or people. Not only does heating water consume a large amount of energy, but if a separate fire is made for wash water, there is all the effort and waste associated with starting that fire. Typically, about 45 g of wood are needed to heat a liter of water to 50°C. Alternatively, about 13 g of charcoal could be used, however it would typically take about 91 g of wood to make the charcoal. If one can use solar energy to heat the water, all that energy is saved, possibly also the effort to start and tend a fire. As will be shown, it is quite easy to heat water with the sun to wash temperatures.

Pre-heated Cooking Water

Heating water to the boiling point for cooking typically consumes about 314 kJ per liter, or 164 g of fuel over an open fire. If one could get the sun to raise the temperature to 70°C, more than half of that energy would be saved. Time to boil would be significantly reduced as well. This would work particularly well if the cooking is done on a charcoal stove. With charcoal, the combustion usually starts out strongly, then tapers off as the fuel is consumed. I have done many charcoal stove tests where the water rapidly heated halfway to the boiling point, then failed to reach the boiling point. With a solar pre-heat, less overall fuel can be used, the water is heated quickly from 70° to the boiling point as the fuel burns strongly, and then there is plenty of fuel left to simmer.

Pre-heating cooking water using solar energy might lead to increased acceptance of fully-solar cooking. In other words, people might think that if the sun can easily heat water more than halfway to the boiling point, perhaps with a little more effort, the sun could do the whole task.

In past experiments, water heated by the sun typically reaches its peak temperature about 2 to 3 hours after solar noon (the time of day when the sun is highest in the sky). The methods shown here for heating water will allow the water to cool somewhat after the peak temperature is reached. Alternatively, the water could be transferred to a more insulated vessel, or the vessel itself could be transferred to an insulated container. That insulated container could be as simple as a blanket or a pile of straw.

Pasteurized Drinking Water

Pasteurization is the heating of a food or beverage (including drinking water) to a temperature sufficient to kill all disease-causing viruses, bacteria, and parasites (together called pathogens). It is not necessary to boil the water, as many people believe. Pasteurization is regularly done to foods such as honey, and beverages such as milk and beer. There is a certain minimum time required which depends on the temperature.

The temperatures needed for pasteurization depend on the microbe. Complex multi-cellular organisms are typically killed by lower temperatures than single-celled bacteria, and viruses usually, but not always, require the highest temperatures. According to the microbiological literature the most heat-resistant pathogen is the Hepatitis A virus, which requires about 6 minutes at 65°C to kill 99.9999% of the virus (6-log reduction) Parry and Mortimer (1984). Somewhat higher temperatures require much shorter times, and lower temperatures for longer times can also be used. Even heating water to 55°C for an hour will kill most, if not all pathogens. Solar heated water will always heat up and cool down slowly.

Most people still believe that it is necessary to boil water to purify it. There are various stories about various lengths of time needed to boil water, sometimes up to an hour. The inconsistency between these stories is a good indicator that they are not based on measurements. Some people even seem to think that water must be boiled prior to using it for cooking.

Why do people think they need to boil their water? Boiling produces a visible indicator, bubbles, that the water has reached a high temperature. Until recently, there was no practical way to know when the pasteurization temperature had been reached. Various types of pasteurization indicators, one developed by me and some developed by others, fill this need, and will be described in a later section.

Inexpensive kits are now available for estimating the contamination level of water. It is possible that people have measured the contamination of their water, boiled it for some amount of time, allowed it to become partially recontaminated, then measured the contamination and found the contamination level lower than before. They might conclude that boiling for a longer time will reduce the contamination further. Clearly, the key to the problem is to not allow the water to be recontaminated, but this is not always easy.

It may also be the case that people boil their water for some amount of time and find that their family has less water-borne disease than before, but still has some disease. The solution might be seen as boiling the water for longer. Generally, to completely eliminate water- and fecal-borne disease, clean water is only the start. Sanitation and hygiene, as well as paying attention to the cleanliness of food, are also important. Children of a certain age explore the world by putting everything in their mouth. If these children are allowed where the chickens have been, no amount of clean water will protect them from some disease.

Reported, a very large number of people in the world boil their drinking water. I could find no research to suggest the total number, but various people estimate it at up to a billion people. If so, and if most of the heating is done on simple stoves and open fires, the carbon dioxide produced by boiling drinking water alone is about 1.2% of the carbon dioxide produced by burning fossil fuels, plus the carbon monoxide and black carbon effects. Even if the heating is done on efficient propane stoves, the total carbon dioxide output is about 0.2% of the fossil fuel total. Bringing water to the pasteurization temperature rather than to the boiling temperature saves at least half of this energy, and if the sun is used to provide the heat, then no fuel is used at all.

The Pasteurization Indicator

If one wants to get people to merely pasteurize their water rather than boiling it, it would be good to confirm that pasteurization was achieved, and therefore some type of pasteurization indicator is needed. At least two types of indicators are commercially available, and other types are being examined.

A good indicator would have the following characteristics. It should be inexpensive and indefinitely reusable, it should be easy to use, it should sense the temperature of the coolest part of the water. It should work in any type or size of water vessel. It should be an indicator, not a thermometer, in the sense that if the water reached pasteurization at any time, the indicator should register that this happened, even if the water has since cooled down. With solar water pasteurization, it is possible that the user would put the pasteurizer out in the sun in the morning, go away to work the fields, and not return until the water has cooled in the evening. The indicator should register that at some point the correct temperature was reached. Finally, the indicator should be able to be read without recontaminating the water.

Experiments have shown that if water is heated from the bottom, as with a cooking pot on a fire, the water temperature will be very uniform, therefore the indicator can be anywhere in the vessel. If a thin layer of water is heated by the sun, its temperature will also be uniform. Deep vessels heated by the sun may have the water significantly cooler at the bottom than at the top, therefore the indicator should go in the bottom of the vessel.

Both of the indicators that are commercially available have all of the desirable features listed above. They have a tube that is sealed at both ends and is partially filled with a wax that melts at 65°. Figure 1 shows the current model of the most popular indicator, available from Solar Cookers International (contact information given at the end of this report).

Figure 1: The Water Pasteurization Indicator (WAPI, or Indicator) available from Solar Cookers Int'l.

The basic design was developed by Fred Barrett and me in 1992 at the request of Solar Box Cookers Int'l (now Solar Cookers Int'l) and it has been improved in a number of ways since then. The wax is colored green for easy visibility. This tube is made of polycarbonate (Lexan) a very tough and heat resistant plastic. A system of small weights pulls the tube to the bottom of the water vessel, but the hollow tube itself is buoyant so it tries to float up. The green wax starts out in the high end of the tube, and if it melts it drops to the low end. The tube is on a string, actually a very thin wire rope, and you use the string to pull the tube out of the water to look at the wax. To reuse the device, it is flipped over and the tube is slid to the other end of the string.

An indicator working on a similar principle is shown in Fig. 2. This is a small glass tube, and it is attached to a metal rod. You would slide the tube to the bottom of the rod and make sure the wax starts out at the top end of the tube. The rod can be bent to fit the size and shape of the vessel. To reuse, the rod is flipped over and the tube is slid to the other end. The glass portion of this system is currently available from Solar Solutions, whose contact information at the end of this report.

Figure 2: The Water Pasteurization Indicator available from Solar Solutions (glass tube only). The rod and spring arrangement turns the simple glass tube indicator into a general purpose indicator that can be used in many different shapes of water vessels.

The rod and spring must be made separately. A group of Ohio State University students devised the rod and spring system, and it works well. Their report with details and part numbers for the spring and rod is available on request.

Another indicator using a memory shape alloy has been the subject of experimentation. It is probably the best design of all. Memory shape alloys have the characteristic that they have a transition temperature. If you bend a memory shape alloy rod below the transition temperature, and then heat it to the transition temperature, it will revert to its original shape. The alloy can be tuned to have a transition temperature around the pasteurization temperature.

Some Practical Considerations to Heating and Pasteurization

The fuel energy saved by using solar energy to heat water is not the only consideration, there is also the time saved, as well as the fuel energy used to start a separate fire, and the energy remaining in the dying fire after the heating task is done. If there is already a fire going, then the additional energy needed to heat the water is the main consideration. In some cases, a fire is left going most of the day (in some regions there is a saying that if there is no smoke coming from the house the woman of the house must be lazy) in which case wash water could easily be heated and cooking water could be preheated with no additional fuel used. Pasteurization could be accomplished by a small fire that was kept burning simply to eliminate the need to relight a fire. Boiling typically can not be achieved by a small fire, and the pasteurization indicator would still be useful.

Regarding pasteurization vs. boiling, even with an indicator it would take a considerable amount of public education to get people to pasteurize, rather than boil their water. The inexpensive test kits mentioned previously could be used to do this. Figure 3 shows a photograph of the results from one type of test kit, the Petrifilm, developed by 3M Corporation.

With the Petrifilm a small amount of water is placed on the film. The film contains food for the bacteria, and if the film is kept warm for about 18 hours each E. coli bacterium in the water sample multiplies about one million-fold and leaves a small blue dot on the film. This method demonstrates not only the presence of E. coli but also the most probable number in the sample. Figure 3 shows the results of water purification, with the raw water in the top row and the purified water in the bottom row. In this case the water was purified by chemical means rather than pasteurization, but the results look the same regardless of the method of purification. To demonstrate the effectiveness of pasteurization, one could do 3 Petrifilm tests, one with raw water, one with boiled water, and one with pasteurized water. The raw water would have lots of blue dots, the boiled water would have none, and the pasteurized water would also have none.

Figure 3: Petrifilm samples before (top row) and after purification (bottom row).

Ways of Producing Hot Water

Sunlight is free but solar collectors are not. The cost of a solar collector per unit area is strongly based on the temperature you want to achieve, with the cost per unit area rapidly increasing if you want higher temperatures. For this application low temperatures are needed, so the idea would be to use the simplest solar collector possible to get reasonable efficiency at the temperature we want. Once the basic design is selected based on the required temperature, make the collection area as large as necessary to get the required energy. For example, if you want to heat a large amount of water, use a simple collector with a large area, if you want to heat a small amount of water, use the same simple type of collector with a smaller area. The following pages show 3 devices for heating water, and any of these 3 devices can be used to fill any of the 3 needs outlined previously. Some devices work better than others to fill certain needs.

Solar Collectors 1-The Pot-Based System

If one has a cooking pot, one can add a sheet of plastic and make a solar collector that will achieve 70°C or better. Figures 4 and 5 show some water heaters I built this past summer using a cooking pot, a sheet of cheap plastic, and some grass.

Figure 4: A small pot-based water heater. The pot holds 6.8 liters of water. The cover sheet is partially folded back for visibility.

The dried grass forms an effective solar absorber. The top layer of grass rapidly gets hot, and the lower layers insulate the top layer from the cooler ground. Previous testing on other types of water heaters showed that the grass was as effective as more highly engineered materials. Heat is transferred to the pot by both convection and direct radiation from grass to pot. The pot is also heated directly from the sunlight striking it. The pot must be dark for best efficiency.

The bottom of the pot is elevated slightly above the top of the grass so that some heat hits the bottom of the pot and prevents a cool water layer from forming on the bottom of the pot. Before the start of the test, basic modeling was done with a simple computer program, which is given in the appendix. This set the basic dimensions of the system, and showed that about 2/3 of the heat transfer to the pot is from the grass to the pot, with the remaining 1/3 being from the sunlight directly striking the pot.

Figure 5: A large pot-based heater, shown without the cover. The pot holds about 29 liters of water.

Johnson and Bryden (2012) report that in the village in Mali that was part of their study, villagers bathe daily using water that is heated in pots from 15 to 30 liters in size. These pots are normally placed on 3-stone fires. Coincidentally, the large pot used in the present study (see Fig. 5) held almost exactly 30 liters of water, thus demonstrating that the sun could be used to heat bathing water using containers that are already available.

The plastic top layer was cheap polyethylene, costing perhaps $0.50 per square meter, probably less from the right source. It was not perfectly transparent, but had a white tint to it. Past experience shows that this material can withstand about 3 months of strong sun before it significantly deteriorates, however the plastic layer need not be perfect for the system to work. Small tears and gaps are not a problem, and some condensed moisture on the inside of the plastic is tolerable. Of course, untinted plastic with no condensation works best.

More expensive ultra-violet stabilized plastic could also be used. The high quality 3-layer plastic used in the AquaPak (described in the next section) which is clear with no tint, UV resistant, and tear resistant, is about $0.62 per square meter, wholesale. If one were trying to introduce this method, one option would be to use the inexpensive plastic first, then if there was demand for a better system, use the better plastic.

The test site was my yard, at 40° N latitude. To get close to tropical sun conditions, testing was done near the summer solstice. Unfortunately, the month around the summer solstice was very cloudy and rainy, and very limited testing was possible. There was basically one sunny day for the small pot and one for the large pot. Test results for the small pot are shown in Fig. 6. The pot achieved 70°C and the amount of water was about 6.8 liters. The water was pasteurized, or could be used a preheated cooking water, or could be mixed with cooler water to form a larger amount of wash water. If one wanted to keep the water hot to use it to cook an evening meal, the pot could be put in an insulated container to keep it hot until the start of the cooking.

As noted in Fig. 6 the peak air temperature was about 34°C on this day. Had the ambient air temperature been higher, the pot would have achieved a higher temperature. The computer model suggests that if the ambient temperature is 10° higher, the final temperature of the small pot is about 7.5° higher, regardless of the water starting temperature. If the starting temperature is 10° higher, the peak water temperature will be 2.5° higher. For the small pot the peak temperature of the water is mostly a function of the ambient temperature, and of course, the amount of sun. It is not such a strong function of the water starting temperature. Different results apply for the large pot, and will be discussed later.

The curves in Fig. 6 show that the top of the water and the bottom of the water are nearly the same temperature. This is common in relatively small containers of water such as these. Figure 6 also shows that the grass if significantly hotter than the water, and that the temperature of the grass responds quickly to the passing of clouds.

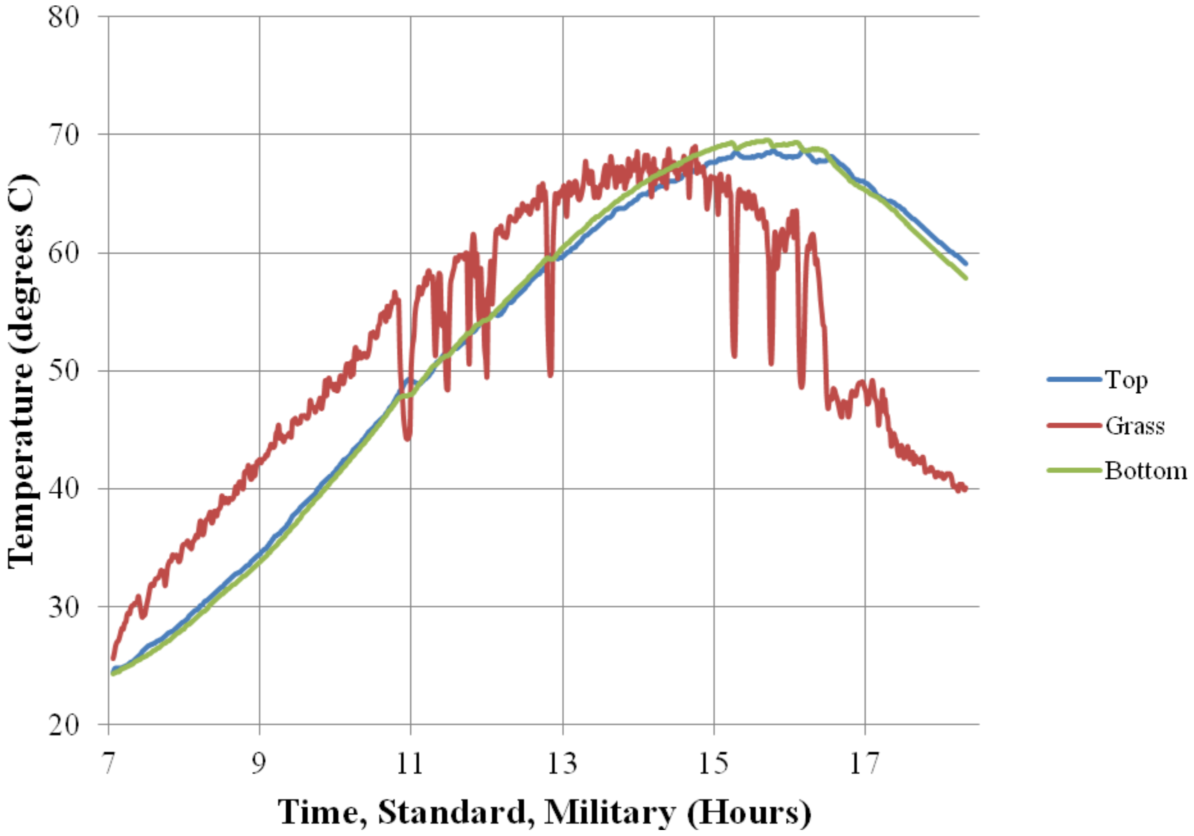

Figure 6: Time vs. temperature plots for July 17, 2013, the only sunny day with the small pot heater. Solar noon was at about 12:25 pm. The peak air temperature on this day was 34°C, the wind was light. The effects of passing clouds can be seen in the rapid drops in the grass temperature. Note that the temperature of the top and the bottom of the water were about the same.

Experimental results for the large pot are shown in Fig. 7. For the large pot test, the weather was very sunny, though the ambient temperature was cooler. The computer model, given in the appendeix, says that if the ambient temperature had been 10 degrees higher, the peak water temperature would be 6 degrees higher, while if the starting temperature had been 10 ° higher the peak water temperture would be 4° higher. As with the small pot, the peak temperature is more dependent on the ambient temperature than the initial temperature.

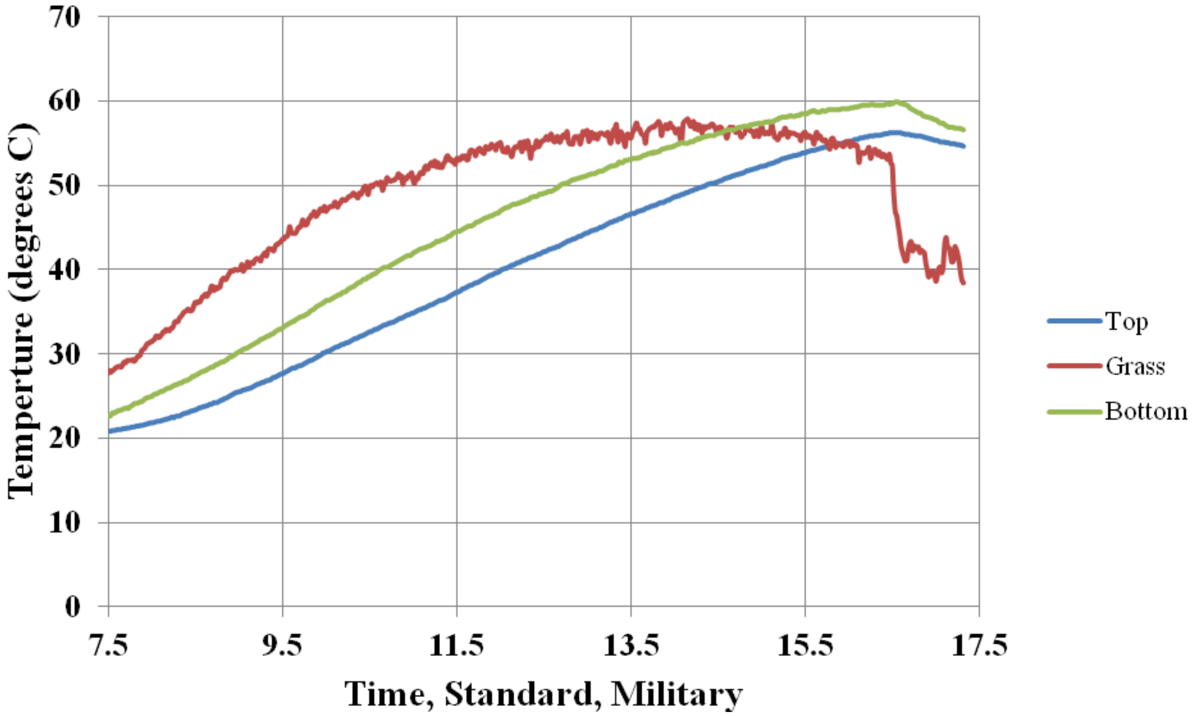

Figure 7: Test results for the large pot heater from July 25, 2013, the only sunny day with the large pot. The weather for this day was sunny until 16:30 hours. Solar noon is at about 12:25. The ambient high temperature was 27°C.

Note that in Fig. 7 the top of the water was significantly warmer than the bottom. If the bottom of the pot were higher above the grass, this stratification would have been reduced, since more heat would be radiating from the grass to the bottom of the pot. If one were trying to pasteurize the water, stratification would be a problem, as the entire water vessel must reach the required temperature for the required time. The pasteurization indicator typically is designed to go in the bottom of the vessel, the coolest part, so the indicator will work properly whether the water temperature is uniform or not.

If one were trying to pre-heat cooking water or heat wash water, then the stratification of the water temperature is not a problem, only the average temperatue is important.

While the weather was sunny on the test date, there was considerable condensation inside the plastic layer, partly a result of the wet ground from previously rainy weather. While a little condensation is not a problem, it is possible that the large amount of condensation present significantly reduced the performance of the collector. Protecting the system from ground moisture may be necessary in wetter climates. This could be done by elevating the system, putting it on a bench, table, or roof, or using a second sheet of plastic. This plastic could be under the grass, where it could be any color and it would be protected from the UV radiation. Or it could be on top of the grass, where it should be black. Previous tests have shown that black plastic on top of grass is not better than bare grass in terms of heat transfer, but could be better in terms of keeping ground moisture out of the system.

Heating Water 2-The AquaPak

The AquaPak was developed by Frank Husson of Solar Solutions in San Diego, CA. It was designed for pasteurization, but can also be used heating wash water or preheating cooking water. The unit is typically used with 2-5 liters, and depending on how hot the water needs to be, multiple batches of water can be heated in a day. For example, if you wanted to pasteurize 5 liters of water, you could probably only get 1 batch per day. But if you wanted to heat wash water to 50°C you could probably get 2 batches of 5 liters each. It would be possible to put one batch in the sun in the morning, use that water for washing in the early afternoon, then put a second batch in the sun in the early afternoon and use it for washing in the evening.

A photograph of the AquaPak is shown in Fig. 8, and a cross sectional drawing provided by Frank Husson is shown in Fig. 9. The AquaPak is a multi-layer plastic bag. The main water-containing bag is UV stabilized polyethylene, and there is a clear layer of bubble wrap on top, and a layer of foam insulation on the bottom. The bubble wrap lets the sunlight through the top into the water, and both the bubble wrap and the foam layer form adequate insulation. A cap is on the bottom of the bag, used for filling and emptying the water. If you use the device as a pasteurizer, the glass portion of the pasteurization indicator shown in Fig. 2 is built into the inside of the cap. The colored wax is in the top of the indicator and is initially visible through the bubble wrap layer. When the wax melts it drops down inside the cap and is no longer visible. The wax is then hidden from view. Figure 9 depicts the wax in the melted condition.

Figure 8: The AquaPak. The bubble wrap in the top insulating layer is visible. Here, the AquaPak lies directly on the ground, where the only bottom insulation is the ¼ inch (6mm) foam layer built into the bottom of the AquaPak. Slightly better performance can be achieved by laying the AquaPak on some insulating material such as grass or leaves.

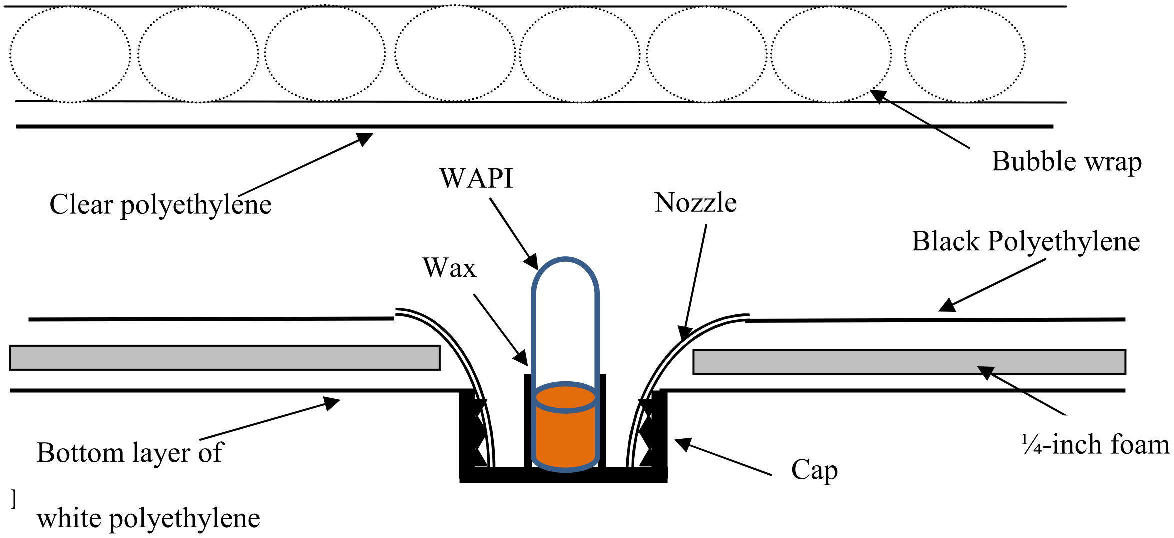

Figure 9: Cross section of the AquaPak.

The plastic of the AquaPak and the seams are surprisingly strong. When new, it can survive a 10-foot drop when filled with water. The plastic does eventually weaken, but the AquaPak will typically last a year, or two if handled gently. The plastic is UV stabilized and will last 3-4 years.

The Pak has a built in handle that can serve a number of practical purposes. The handle makes the Pak easier to carry, and it allows for the possibility that many Paks could be carried at once using a long stick or pipe or pole. One could walk to the water source with as many as 8 Paks, fill them all, then carry them home with the pipe carried across the shoulders. The Pak also comes with a filter for improving the turbidity of the water, and chlorine tablets for days when the sun doesn't shine.

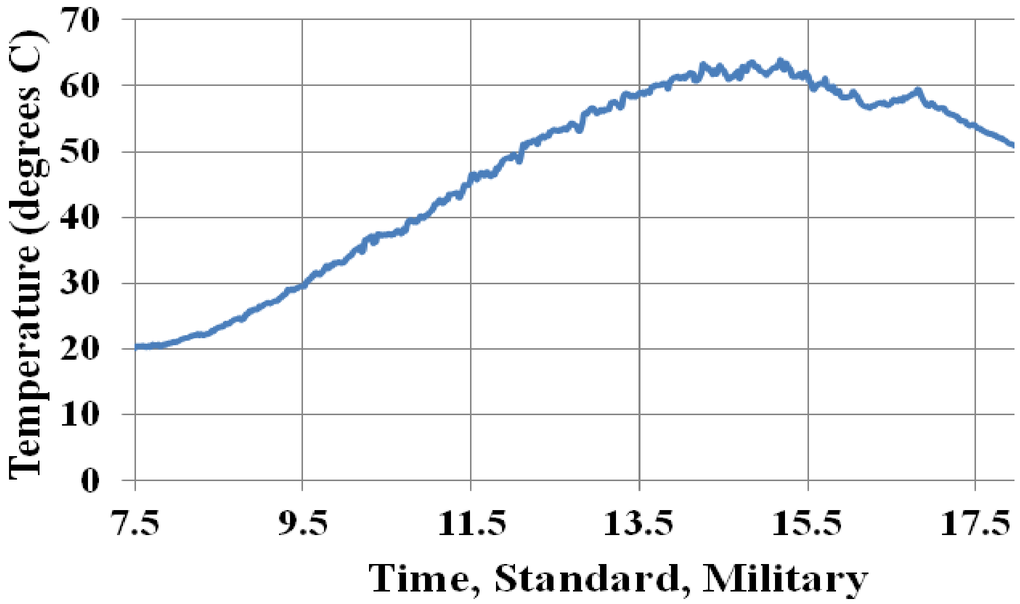

Figure 10: Test results for the AquaPak with 5762 g of water on August 4, 2013. The weather on this day was partly cloudy with a high temperature of 24°C. Pasteurization was achieved, as the water was at or above 60° for 1 ½ hours. The AquaPak was placed on a bed of plastic sheets to provide a little extra ground insulation, which probably led to a small improvement in performance. On a warmer day, or on a sunnier day, pasteurization would easily have been achieved.

The AquaPak is currently available from Solar Solutions, the contact information for which is listed at the end of this document. The current cost is about $20, made in San Diego. Frank's plan is that factories could be set up in developing countries which, at developing world labor rates, would allow the Pak to be made for about $2. The machinery required to seal the seams of the Pak is not all that expensive, so a factory could be set up for a modest amount of money. About $40,000 would cover the machinery and a large supply of raw materials. To date, this has not happened.

Other water heaters could be built with similar bag concepts. One experimental unit was built that was larger in area than the AquaPak, had an inflatable top cover rather than bubble wrap, and had no foam insulation on the bottom. When placed on a bed of grass similar to the pot heaters in Figs. 4 and 5 it outperformed the AquaPak in both volume of water and temperature. More information is available about this bag pasteurizer, the AquaPak, and other small pasteurizers in Husson and Andreatta (2003).

Heating Water 3-The Solar Puddle

The solar puddle was developed in 1994. It was intended as a pasteurizer, but can also be used for washing water or pre-heating cooking water. The idea is to get as large an area as possible for the least amount of money possible.

The basic configuration of the solar puddle is shown in Fig. 11. This form is built into the ground, and the only purchased materials are the plastic sheets and the pasteurization indicator, if used. Fancier versions can be built on table tops with wooden sides. The puddle can be built in any shape, square, round, rectangular, and the size is limited by one's ability to keep the water layer of uniform depth. The insulation can be wads of paper, grass or leaves. The insulation should not be too soft, otherwise it will compress non-uniformly under the weight of the water.

Typically, 4 layers of plastic are used. There are 2 layers under the water. Two layers are used because cheap polyethylene tends to have very small holes every now and then. If high quality plastic were used, such as with the AquaPak, perhaps only one bottom layer could be used. On top of the water there is a single clear layer, and its purpose is to keep the water from evaporating. There is then an air gap, with a final layer of plastic on top of the air gap. The top layer can be in the shape of a tent, which may repel rain. One could add a 5th layer of plastic to form a second air gap.

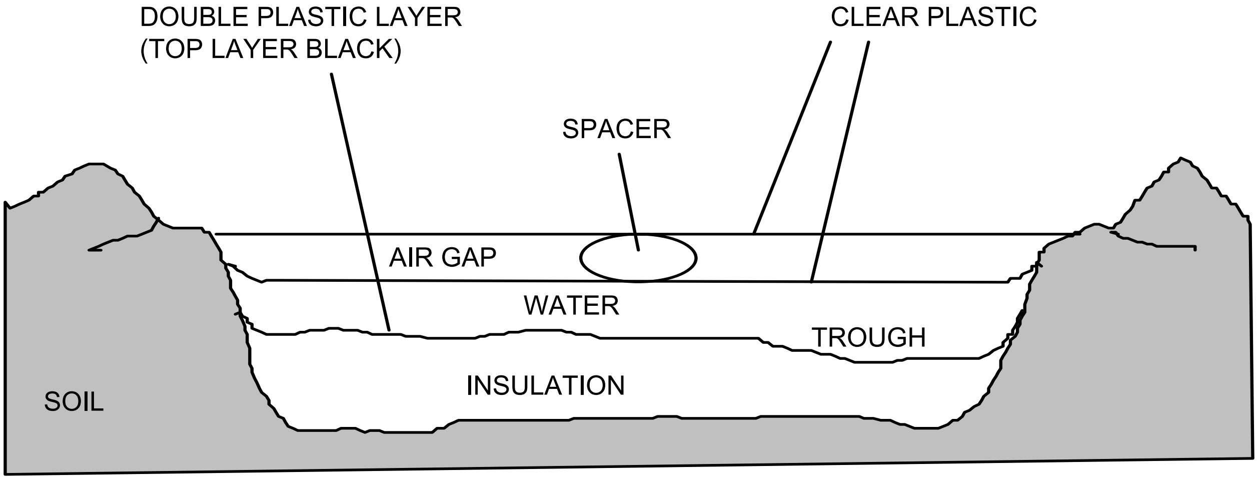

Figure 11: Cross section of the basic solar puddle, which is built into the ground. It can also be built on a bench or roof. Horizontal dimensions are compressed for clarity, but are typically 1 m by 1 m. A pasteurization indicator would be placed in the area of the trough.

The solar puddle was tested in 1994 in Berkeley, California. Typically, the sun in Berkeley is strong, but summer temperatures are moderated by the Pacific Ocean. The puddle worked well, even under nonoptimal conditions. Tears in the plastic top sheet and condensation under the top sheet did not prevent the puddle from working. The size tested was about 1 m by 1 m.

Figure 12: Photograph showing two versions of the solar puddle built on a platform. The version on the right is the standard version, normally with 4 layers of plastic but the top layer has been removed. The version on the left has the top two layers of plastic replaced by bubble wrap. Both versions perform about the same.

In order to present more detailed results, and to further study the solar puddle, a computer model was developed. The code for this model is shown in the appendix. The results of the model generally agree with the experimental results from the 1990's. With this computer model one can look at the effects of initial water temperature, air temperature, how fast the water cools down after the peak temperature is reached, and the effects of key variables.

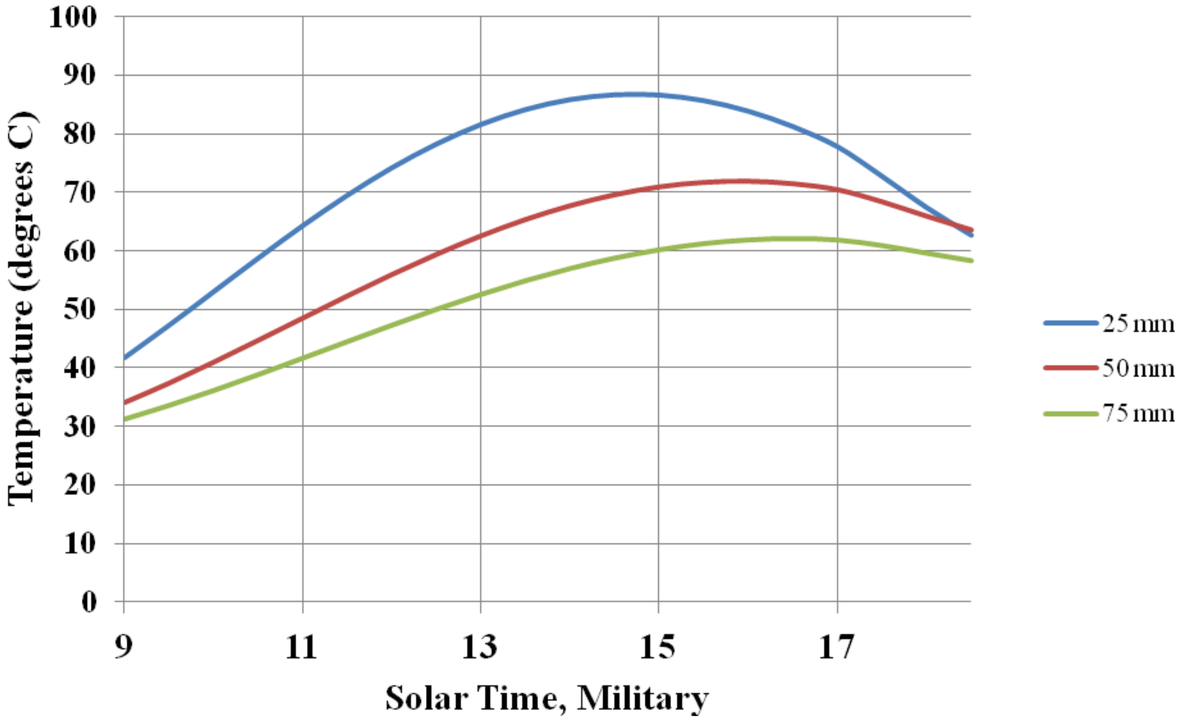

Figure 13: Solar puddle calculated results for 3 different water depths. The time on the horizontal axis is solar time, and the calculations assume a 12-hour day. Thus, the sun rises at 6 hours and sets at 18 hours. The assumed weather conditions are sunny skies and a peak ambient temperature of 35°C.

We can see in Fig. 13 that the thinner water layers give a higher peak temperature, as would be expected. The peak temperatures are well above 80° for the thin water layer and for the weather conditions assumed. This agrees with experimental results, which showed that over 80° could be achieved with good sunshine and peak air temperaures of 30° or so, with a thin water layer. A solar puddle of 1 square meter area with a 25 mm water depth would produce 25 liters of water per day. For the thin water layer, the water temperature is already over 80° by early afternoon, thus, this might be an efficient preheater for a meal at roughly noon time. One would not need to worry about the water cooling down.

For the thicker water layers the water doesn't heat up as much, but doesn't cool down as fast. One could always drain the water from the puddle at a time near when peak temperature was achieved and store the water in an insulated container. While the thickest water layer doesn't fully achieve the 65° pasteurization temperature, it is above 60° for over 2 hours and even Hepatitis A would be killed.

The peak temperature achieved with a puddle depends mostly on the thickness of the water layer and the amount of sunshine, and to a lesser extent on the air temperature. For the 75 mm layer the peak temperature depends on the both of these things. A 10° decrease in air tempeature gave roughly a 5° decrease in peak water temperture, and a 10° decrease in initial water temperature gave a 5° decrease in peak water temperture. For the 25 mm layer, the initial water temperature made little difference, and a 10° decrease in air temperature gave a nearly 10° decrease in peak water temperature.

Typically, if you wanted wash water you would use a very thick layer of water. For pasteurization, an intermediate thickness would be used, along with a pasteurization indicator. For pre-heating cooking water, a thinner layer would be used, and the water could be drawn directly from the puddle when starting the fire for a mid-day meal, or drawn into the cooking pot and put in insulation for an evening meal.

The model here assumed that 50 mm of insulation are present under the puddle. The calculations show that with this amount of insulation, very little heat goes through the bottom of the puddle. There is little benefit to increasing this insulation, and the thickness of this insulation could be decreased if needed for practical purposes. One practical problem that can occur with insulation is that if the insulation is too soft, deep spots in the water layer will contain more water, which compresses the insulation further in that region, which brings in more water, which compresses the insulation in that location even more.

More details about solar puddles are given in Andreatta (2001) and Husson, Andreatta, and Hankal (2005). A purely analytical model (not requiring a computer) is presented in Andreatta (2001) however, that model is probably not as accurate as the computer model given here.

A Final Application of Solar Thermal Energy-Fecal Sludge Management

I have not studied this application either experimentally or theoretically yet, but it will be included here to pique the thinking of the reader. In the world over 2 billion people do not have access to proper sanitation facilities. Human feces, aside from being smelly and nasty to deal with, contains a vast number of pathogens. Some of these pathogens are worms that live in moist soil or water and enter the body through the skin, particularly the soles of the feet. Providing clean drinking water will do nothing to deter these pathogens, so sanitation is required even when clean drinking water is available.

In a previous section the process of pasteurization of drinking water was described, and it was shown that pathogens in water are killed by temperatures well below the boiling point and at temperatures that are easily achievable with the sun. It should be possible to decontaminate feces by similar temperatures.

Fecal sludge management systems not dependant on sewers have been shown to be much more cost-effective than sewers in parts of Africa, and decentralized systems have a number of practical advantages, Dodane, et al. (2012). Decontamination close to the source could be an important step in fecal sludge management, regardless of what is done with the sludge afterwards. It will be left to the future to determine the best way to do this, hopefully also in a way to reduces the mess and suffering around fecal sludge management, and possibly even turning the fecal sludge into something useful for fertilization or energy.

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Contact Information

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For Glass WAPIs and AquaPaks,

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(858) 695-3806 extension 4703

Computer Codes

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{Solar Puddle Analysis, Temperatures in Kelvins unless noted}
d=.075  {Water depth in meters}
rho=990000  {water density, grams per m^3}
tend=endhour*3600  {Endhour is specified in a table}
cp=4.186
To=25+273+10*sin(2*pi*(time-7200)/24/3600) {air temperature, sine wave with amplitude 10, peaking 2
hours after solar noon}
Tinit=25+273  {Initial water temperature, also assumed equal to ground temperature}
alpha=.95
k=.04  {conductivity of bottom insulation}
sigma=5.67e-8
q=750*sin(2*pi*time/24/3600)  {Time equals 0 at dawn, assume 12 hour day}
qpp=step(q-150)*q  {Truncate the solar curve when the sun is low on the horizon}
v=2  {wind velocity, meters per second}


hco=2.8+3*v  {Comes from Ref.}
u=1/(R1+R2+R3)
R1=1/(hc1+hr1)
hc1=5
hr1=(Tw-20)^3*4*sigma
R3=1/(hco+hro)
hro=(Tw-40)^3*4*sigma

{Use this section for single glazing, that is one layer of plastic directly above the water with one air gap, and
one layer of plastic directly above that..}
tau=.9^2
R2=0

{Use this section for double glazing, where there are 2 air gaps and an extra air gap.}
{tau=.9^3
R2=1/(hc2+hr2)
hr2=(T-30)^3*sigma*4
hc2=5}

dTwdt*d*rho*cp=qpp*alpha*tau-u*(Tw-To)-(Tw-Tinit)*k/.05

Tw=Tinit+integral(dTwdt,time,0,tend,60)
Twc=Tw-273  {Convert to degrees C}
{Reference refers to p. 167 of Solar Energy:  The State of the Art, ISES Position Papers, Edited by Jeffrey
Gordon, International Solar Energy Society, 2001, James & James (Science Publishers) Ltd.}
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{Analysis of Pot based Heaters.  Temperatures are in Kelvins unless noted.}

{These parameters represent large pot}
{r=.18
a=.8
h=.28
h1=.1}

{These parameters represent small pot}
r=.12 {radius of pot}
h=.15  {depth of water in pot}
a=.25  {radius of grass area beyond pot}
h1= .1  {height of bottom of pot above top of grass}

V=1000*r^2*pi*h {Liters}
m=1000*V   {grams}
cp=4.186
tau=.9
alpha=.95
sigma=5.67e-8
F12=(r^2+r*(h+sqrt(a^2+h1^2)-sqrt(a^2+(h+h1)^2)))/(r*h+r^2) {Approximate radiative view factor from 1 to 2}
A1=pi*r^2+pi*r*h
A2=pi*(r+a)^2
A3=2*pi*sqrt(1+(a/(h+h1))^2)*(h+h1)*(r+a/2)
F23=1-F12*A1/A2  {Radiative view factor from 2 to 3}
Tinit=20+273
hco=8.8 {Follows formula that hco=2.8+3V, where V is wind speed in m/sec.  Assumed wind is 2 m/sec. Comes from Reference}
hro=4*sigma*Tbar^3
hc=3  {Comes from Reference, assumes a large h dimension.}
hc4=5  {Comes from Reference, assumes a fairly small separation between lid and glazing.}
tend=3600*n  {n specified in table}

qmax=750
omega=2*pi/24/3600
qpph=max((qmax+100)*sin(omega*t)-100,0)  {q" falling on horizontal plane, half sine wave, shortened at the ends by shadows}
qppv=qmax*abs(cos(omega*t))  {q: hitting vertical surface, half cosine wave, does not include shadows}
To=273+25+10*sin(omega*(t-2*3600))  {half sine wave, delayed by 2 hours, average 25, 0-peak of 10}
Tbar=70+273  {"Typical" temperature used in radiation calculations}

{Energy Balance on pot, 1}
r*h*qppv*tau*alpha+qpph*pi*r^2*tau*alpha-(T1-T2)*4*sigma*Tbar^3*F12*A1-(T1-T2)*hc*A1-(T1-T3)*4*sigma*Tbar^3*(1-F12)*A1-hc*pi*r*h*(T1-T3)-pi*r^2*(T1-T4)*(hc4+4*sigma*Tbar^3)=m*cp*dTdt
Qdirect=r*h*qppv*tau*alpha+qpph*pi*r^2*tau*alpha
Qindirect=(T2-T1)*4*sigma*Tbar^3*F12*A1+(T2-T1)*hc*A1-(T1-T3)*4*sigma*Tbar^3*(1-F12)*A1-hc*pi*r*h*(T1-T3)

{EB on grass, 2}
qpph*tau*alpha*pi*(a+r)^2-r*h*qppv*tau*alpha-qpph*pi*r^2*tau*alpha+(T1-T2)*4*sigma*Tbar^3*F12*A1+(T1-T2)*hc*A1-(T2-T3)*4*sigma*Tbar^3*F23*A2-(T2-T3)*hc*A2-(T2-Tinit)*A2*.03/.05=0
{1st term above is total energy hitting glazing.  2nd and 3rd terms are energy hitting top and sides of pot, and therefore not hitting surface 2.  Last term is energy conducted through to ground.}
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```
{EB on glazing on sides of structure, 3}
(T2-T3)*hc*A2-(T3-To)*(hco+hro)*A3+F23*A2*(T2-T3)*4*sigma*Tbar^3+(T1-T3)*4*sigma*Tbar^3*(1-F12)*A1+hc*pi*r*h*(T1-T3)=0

{EB on glazing on top of pot, 4}
(T1-T4)*(4*sigma*Tbar^3+hc4)-(T4-To)*(hco+hro)=0

T1=Tinit+integral(dTdt,t,7200,tend)   {Start at 2 hours after dawn}

Tc=T1-273  {Water temperature in degrees C}
{Reference refers to p. 167 of Solar Energy:  The State of the Art, ISES Position Papers, Edited by Jeffrey Gordon, International Solar Energy Society, 2001, James & James (Science Publishers) Ltd.}
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