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Construction and Performance Testing of a Mixed Mode Solar Food Dryer for Use in Developing Countries

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Construction and Performance Testing of a Solar Food Dryer

for Use in Developing Countries

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Master of Science

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ABSTRACT

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This study details the construction and performance testing of a mixed mode solar dryer using a combination of direct and indirect solar energy to dry food. One major benefit of this dryer design is its construction. It was simple to construct and was made with low cost materials, to make it feasible for use in developing countries. Previous research has identified several design factors that affect performance and efficiency: product loading density, number of trays, position of the absorber, and chimney type. Performance testing showed that chimney airspeeds were not affected greatly by modifying the design aspects of the dryer, with only a small increase occurring when using a box-type chimney. Overall the temperatures were mostly dependent on irradiance, but using a collector-type chimney generally resulted in higher temperatures throughout the dryer. The RH change across the dehydrator was most affected by the number of trays, but the chimney type did have an effect on the RH right at the chimney exit. Efficiency testing showed that product loading density on the trays was tested at 40% and 60% capacity; there was no statistical difference observed for efficiency between the two levels. Our results show that the dryer was more efficient when using the maximum number of trays. The lowest position of the absorber (5 cm from the ground) was found to be most efficient. A box-type chimney was significantly more efficient than the collector-type chimney in this full factorial study.

Keywords: solar dryer, efficiency, performance testing, dehydration, solar collector

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Drying

Solar energy has been used to dry foods for thousands of years. Solar energy translates to heat during the drying process, so whether product is laid out in the sun (ambient) or placed in a dryer, the heat for drying comes from the same source. Drying involves extraction of moisture from the product by heat and removal of that moisture by a flowing air mass (Ekechukwu and Norton, 1999). According to Ekechukwu (1999), thermal drying involves vaporization of water within a product by heat and then evaporation of that moisture from the product. Drying continues until the vapor pressure of the moisture within a product equals the vapor pressure of the atmosphere, or equilibrium moisture content. Ekechukwu (1987) has shown that drying under ambient conditions is slow because the process is controlled by the environmental factors of relative humidity and heat, and thus is dependent on local weather conditions. This problem is compounded when a region has a high relative humidity because the equilibrium moisture content will be higher and products cannot be dried to the desired levels (McLean, 1980). A solar dryer is designed to increase the heat within the system, which in turn increases the vapor pressure of the product. This increases the moisture carrying capacity of the air within the dryer, inherently speeding up the drying process because the equilibrium moisture content is much lower.

Components of a Dryer

Solar dryers have two basic parts: a solar collector, and a drying chamber. The solar collector has within it an absorber that collects the heat from the sun's rays. The heat from the collector is carried by convective currents (in a passive dryer) to the drying chamber. The drying chamber is where product is placed to have moisture removed from it. Product is placed so that heated air can flow around it to carry moisture away from it.

Categories of Dryers

Solar dryers can be separated into two basic categories: passive dryers, and active forced-air dryers (Jairaj and others, 2009). The difference is based on the airflow within a dryer. Passive dryers rely solely on the convective currents created by heat to move the air through them (figure 1). Active dryers have a fan to force the air through them. Within these two main categories, dryers are also grouped according to the method they use for trapping heat from the sun. Direct solar dryers allow solar radiation to fall directly on the drying chamber and the product to be dried. Indirect dryers have a solar collector that absorbs solar energy, the heat produced is then moved across the product by airflow (Simate, 2003). Yet another type of dryer is a mixed-mode dryer, which – as the name implies – uses both direct and indirect solar energy. A solar collector accounts for much of the heat entering the drying chamber, but the drying chamber itself is open to solar radiation as well. All three of these types of dryers can be either passive or active dryers (Ekechukwu and Norton, 1999).

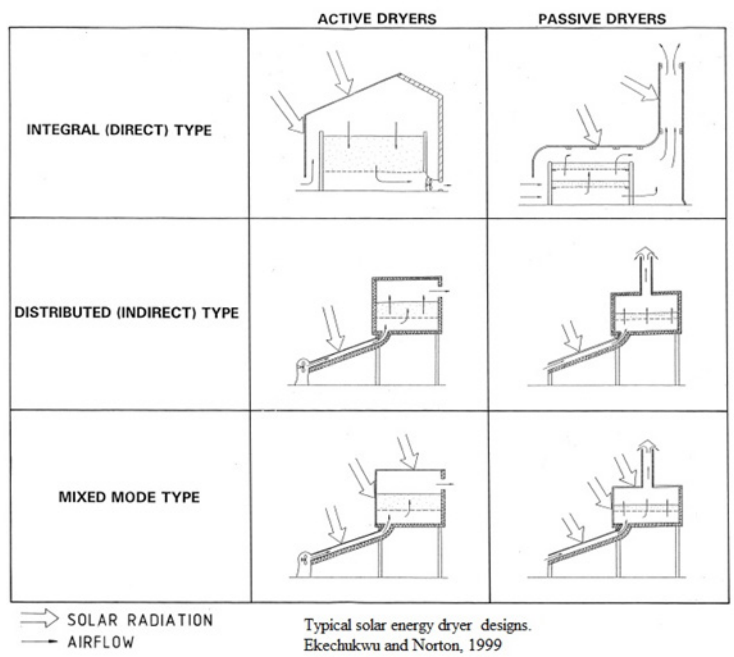


Figure 1: Solar dryer types

Efficient Mixed-mode Dryer Design

A mixed-mode dryer (figure 2) combines the features of direct and indirect dryers. This combination furnishes the necessary heat required for the drying process and works especially well for dryers with larger product loads (Fudholi and others, 2010). The indirect side of the dryer is made up of a collector. Collectors need to be efficient in order to effectively transfer heat from the sun to the air within the dryer.

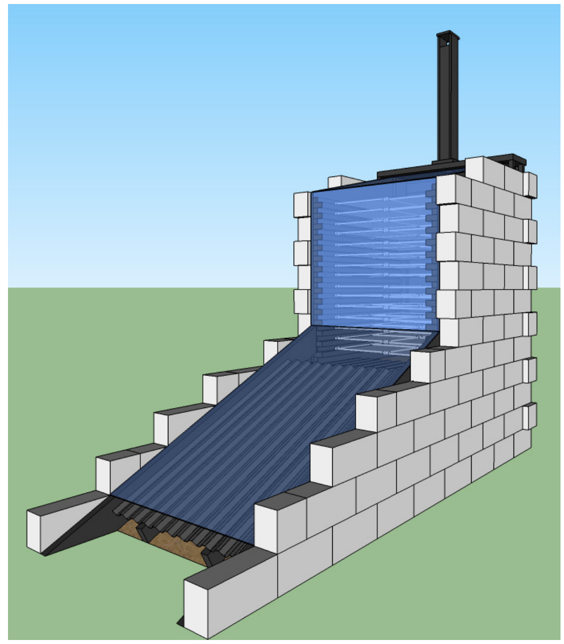
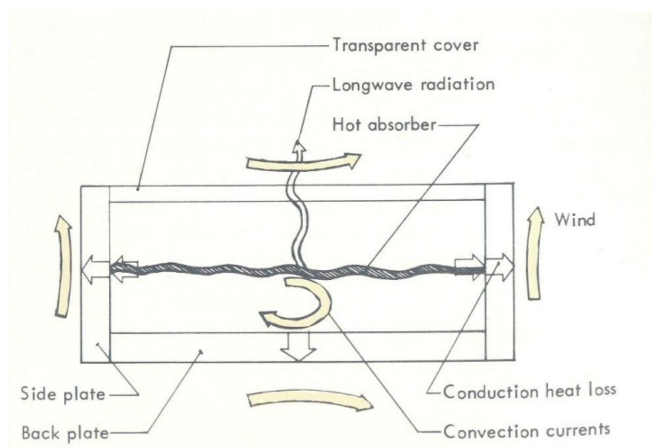


Figure 2: Mixed mode solar dryer

The most efficient collector is one that traps almost all of the incoming solar radiation. The angle of the sun perpendicular to the collector is called the angle of incidence. Keeping this angle as close to zero as possible will allow the absorber to capture as much of the solar radiation as possible. Some modern solar dryer designs will actually track the sun and make adjustments to maintain an angle of incidence of 0°. Mwithiga and Kigo (2006) found that tracking the sun did not increase dryer efficiency enough to warrant the extra cost. Tracking the sun also reduces the size of the dryer, because the collector has to be small enough to be mobile, simultaneously reducing the amount of product the dryer can produce.

Most dryers are stationary and aligned so that they track the sun in one direction. In the Northern hemisphere above 15°N dryers should be facing south (Midwest Plan Service, 1980; Ekechukwu and Norton, 1999; Fudholi and others, 2010). Between 15°N and 15°S dryers typically face East-West (Amouzou and others, 1986). The reason for this is to get the most amount of exposure to the sun for the collector. Midwest Plan Service (1980) also recommends setting the tilt angle of a fixed collector so that the angle of incidence will be near 0° at noon. Because the sun's altitude varies with the latitude and time of year, the angle of incidence will vary depending on location and the season in which the dryer will be used. It is also recommended to set the tilt angle of a collector equal to the latitude if the dryer is to be used year-round. A dryer on the equator would be aligned East-West and have a tilt angle near 0°. Ekechukwu and Norton (1999) found that a small angle is required for rain runoff (between 5° and 8°). This slight angle will also promote airflow toward the drying chamber, as heat rises.

The collector is primarily comprised of an absorber which collects solar energy and releases it to the surrounding environment as heat. A good absorber in a solar collector will absorb a high percentage of incoming solar radiation and lose little thermal energy to the surroundings but be able to transfer the absorbed energy efficiently to the air within the collector (figure 3, Midwest Plan Service, 1980). Absorbers are made of dark materials because they have a higher absorptance. The only downside to most dark materials is that they have high longwave emittance. Longwave emittance is the energy that an absorber will give off to its surroundings after it reaches a higher temperature than its surroundings. Hachemi (1999) showed that ideal absorbers are treated so they have high absorptance with low long wave emittance, these are termed selective absorbers. While it is possible to get absorbers made with these characteristics, the cost usually outweighs the benefit. Midwest Plan Service (1980) observed that regular galvanized steel naturally has a higher absorptance (0.80) and a low longwave emittance (0.28). This



Heat Losses from a Solar Collector. Midwest Plan Service, 1980.

Figure 3: Collector heat loses

coupled with its low cost makes it a likely candidate for efficient absorbers.

Absorber to air heat transfer depends on the velocity of the air and the absorber surface area. The ideal air velocity is between 150m/min and 300m/min (Midwest Plan Service, 1980). Above 300m/min there is not enough heat buildup for efficient drying. Joudi and Mohammed (1985) showed that as airflow around a collector increases the temperature of the collector decreases, slowing the drying process. In order to raise the temperature of the collector a good absorber is needed. The shape of the absorber can increase its efficiency greatly.

Simple absorbers can be made out of flat metal plates (Hachemi, 1999). Yeh and others (2000) found that increasing the absorber surface area will also improve heat transfer. In order to increase the area of a flat plate absorber the entire collector must be enlarged. A more efficient method for increasing absorber area without making the entire collector bigger is to change the geometry of the absorber itself. This can be done by using corrugated, crimped or finned absorbers (figure 4, Joudi and Mohammed, 1985; Karim and Hawlader, 2006). These shaped absorbers will increase the absorbance due to their enlarged surface area, and the additional geometry will reflect solar radiation around the chamber allowing for increased opportunity for absorption (Karim and Hawlader, 2006).

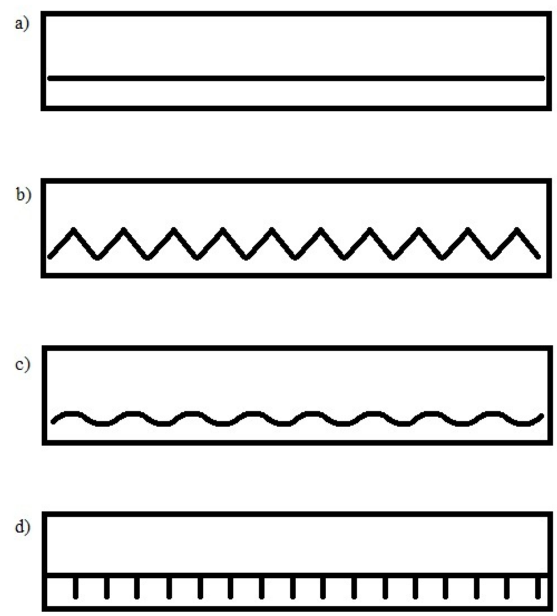


Figure 4: Cross section of absorber shapes.
a) flat plate b) “v” grove
c) corrugated d) finned

There are many materials for collector coverings but absorbers covered by a transparent material like glass with a high transmittance have been shown to be most effective (Midwest Plan Service, 1980). Glass has a high transmittance but has several drawbacks, including being brittle and heavy, leading to the necessity to replace it more frequently than other materials. Polycarbonate coverings are becoming increasingly popular, though a major drawback is that all plastics will deteriorate over time when exposed to UV radiation (Amouzou and others, 1986). The rate of this deterioration is dependent on the amount of UV radiation the polycarbonate is exposed to, but the average degradation is a loss of 10% admittance over the space of seven years (Midwest Plan Service, 1908). Regardless of the material used, this covering should be placed away from the absorber creating a box-like collector to allow easy airflow between the absorber and the covering (Bolaji, 2005). Allowing for airflow across both the top and bottom of the absorber will further increase the rate of drying within the drying chamber according to Yeh and others (1999).

Another factor that can increase collector efficiency is to place the collector above a material that has a high thermal storage capacity. When Chauhan and others (1996) added thermal storage to their solar dryer design, they reduced the drying time of a grain bed from 3 days to 31 cumulative hours (18 sunlight and 13 off-sunlight hours). During the sunlight hours, the absorber not only heats the air but the storage material as well. During the off-sunlight hours the storage material emits both radiant and convective heat back into the dryer. This continues the drying process even after the sun has gone down. Many different materials can be used for thermal storage including: water, rock, sand and concrete. The amount of sensible heat that may be stored can be determined using the following equation:

$$\underset{(Btu)}{\textit{Sensible heat storage}} = \underset{(lb)}{\textit{Weight of storage material}} \times \underset{(Btu/lb_m\cdot°F)}{\textit{Specific heat of storage material}} \times \underset{(°F)}{\textit{Temperature rise of storage material}}$$

Ideally the temperature of the storage material shouldn't rise much more than air within the dryer. This keeps losses of heat to the environment to a minimum (Midwest Plan Service, 1980). One method to reduce heat loss to the environment from the storage material is to place the storage on top of an insulator material. Ayensu and Asiedu-Bondizie (1986) found that a thin (5cm) layer of straw below the storage material (granite) acted as a sufficient insulation to keep losses to the ground minimized.

Optimally the drying chamber will have high airflow and a much greater temperature than the surrounding environment. An efficient indirect collector will create a high temperature within the drying chamber. One problem with indirect designs is that the product in the dehydration chamber closest to the exit from the collector will dry faster than the rest of the product in the chamber (Vlachos and others 2002). As drying chamber efficiency generally depends on the amount of airflow through the chamber, product spacing and loading must be taken into account to determine efficiency (Russon and others, 2009). The benefit of having a mixed-mode dryer is that the dryer is not solely dependent on the indirect collector to provide heat transfer. The drying chamber collects solar radiation in addition to the collector, further increasing airflow by convective currents and elevating the temperature of the drying chamber. The drawback of direct solar drying is that direct contact with UV rays can damage the quality of the product being dried (Simate, 2003). This can be countered by using a glazed covering, which will still have a high admittance but keep some of the more harmful UV rays off of the product.

Product within the drying chamber is placed on trays. The number and size of trays within a dryer will depend mostly on the geometry of the drying chamber. Russon and others (2009) optimized an indirect natural convective flow solar dryer and found that the drying rates improved when the number of trays was less than the maximum number of trays the dryer could hold (15 as opposed to 20).

Trays are built out of materials that allow for airflow through the dryer. Materials that have been tested for trays include wire mesh, woven bamboo mats, nylon netting and cloth (Ekechukwu and Norton, 1999; Fudholi and others, 2010). Most designs to date have utilized wire mesh, but the moisture in the product has a tendency to rust the mesh over time (Fudholi and others, 2010). Nylon netting has the advantage in that it will not rust and can be food grade. Both nylon netting and wire mesh can be ordered in a variety of styles, some of which allow more air through than others. The size of the holes within the mesh depends on what the dryer is going to be used for. A smaller size mesh will be used for grains, larger mesh for fruits, vegetables and meats (Fudholi and others, 2010).

Moisture is removed from the food and carried away in the hot air flowing through the dryer. In convective airflow dryers this process is generally aided by adding a chimney, generating a buoyant force on the air (Ekechuwu and Norton, 1999). Buoyancy is the driving force that makes hot air rise. As air is heated it expands, and becomes less dense. This change in density causes the cooler space around it to force the less dense air upwards until the net force is neutralized. A chimney on top of the dryer has been shown in multiple studies to increase this buoyant force and promote better airflow (Fudholi and others, 2010). Many designs utilize chimneys painted dark to keep the chimney warm and maintain airflow (Ekechuwu and Norton, 1999). Madhlopa and others (2002) found that a chimney improves airflow through a dryer, but increasing the height of the chimney has an even greater effect on airflow. In the optimization study done by Russon and others (2009) this same effect was observed. Another type of chimney that has been used with some success in solar dryers is a solar collector chimney. This chimney is faced toward the sun like the collector. The side facing the sun is covered in a transparent material and the side opposite is painted black to create an absorber. This chimney design is for all intents and purposes another collector that helps draw air through the drying chamber (Sakonidou and others, 2008).

In summary a mixed mode solar dryer is made up of a collector, a dehydration chamber and usually a chimney. A collector is made up of an absorber and is covered by a transparent material with a high transmittance. An efficient absorber can be made of many different materials but usually has corrugations or bends in it that allow for an increased surface area, while maintaining a small overall area. A collector can also use a thermal storage material to continue heat transfer into the dryer after the sun has set. The dehydration chamber of a mixed mode dryer is covered by the same covering material as the collector in order to allow direct heating of the dehydration chamber. The dehydration chamber is where product is placed in order to dry it. Product is usually placed on trays that allow for airflow through them. Airflow through the dryer is one of the most important factors for maximizing efficiency. A chimney generally increases rate of airflow through the dryer.

References

Amouzou K, Gnininvi M, Kerim B. 1986. Solar drying problem in Togo: research and development of solar drying in Africa. Solar drying in Africa: Proceedings of a workshop held in Dakar, Senegal 252-271.

ASHRAE Standard 93-2003. Methods of testing to determine the thermal performance of solar collectors. Atlanta, Georgia.

Ayensu A, Asiedu-Bondizie. 1986. Solar drying with convective self-flow and energy storage. Solar and Wind Technology. 3(4):273-279.

Bolaji BO. 2005. Development and performance evaluation of a box-type absorber solar air collector for crop drying. J Food Technol. 3(4):515-600

Ekechukwu OV. 1987. Experimental studies of integral-type natural-circulation solar-energy tropical crop dyers. Ph.D. thesis. Cranfield Institute of Technology, United Kingdom.

Ekechukwu OV. 1999. Review of solar-energy drying systems I: an overview of drying principles and theory. Energ Convers Manage. 40:593-613

Ekechukwu OV, Norton B. 1999. Review of solar-energy drying systems II: an overview of solar drying technology. Energ Convers Manage. 40: 615-655

Fudholi A, Sopian K, Ruslan MH, Alghoul MA, Sulaiman MY. 2010. Review of solar dryers for agricultural and marine products. Renewable and Sustainable Energy Reviews. 14:1-30.

Hachemi A. 1999. Technical note: Comparative study on the thermal performances of multi-pass flat-plate solar air heaters with external recycle. Renewable Energy. 30(10):1601-1621

Jairaj KS, Singh SP, Srikant K. 2009. A review of solar dyers developed for grape drying. Sol Energy. 83:1698-1712.

Joudi KA, Mohammed AI. 1985. Experimental performance of a solar air heater with a “V” corrugated absorber. Energ Convers Manage. 26(2):193-200.

Karim MA, Hawlader M. 2006. Performance investigation of flat plate, v-corrugated and finned air collectors. Energy. 31(4):452-470

Madhlopa A, Jones SA, Saka JDK. 2002. A solar air heater with composite absorber systems for food dehydration. Renew Energ. 27(1)27-37

McLean KA. 1980. Drying and storage of combinable crops. Suffolk Farm Press.

Midwest Plan Service. 1980. Low temperature & solar grain drying handbook. Ames, Iowa : Midwest Plan Service.

Mwithiga G, Kigo SN. 2006. Performance of a solar dryer with limited sun tracking capability. J Food Eng. 74(2):247-252.

Othman MYH, Sopian K, Yatmin B, Daud WRW. 2006. Development of advanced solar assisted drying systems. Renewable Energy. 31(5):703-709.

Russon J, Steele F. 2009. Optimization of a convective air flow solar food dryer. Int J of Food Eng. 5(1) Article 8

Sakonidou EP, Karapantsios TD, Balouktsis AI, Chassapis D. 2008. Modeling of the optimum tilt of a solar chimney for maximum air flow. Sol Energy. 82:80-94

Simate IN. 2003. Optimization of mixed-mode and indirect-mode natural convection solar dryers. Renew Energ. 28:435-453

Tiris C, Ozbalta N, Tiris M, Dincer I. 1994. Experimental testing of a new solar dryer. Int J Energy Res. 16(4):483-491.

Vlachos NA, Karapantsios TD, Balouktsis AI, Chassapis D. 2002.Design and testing of a new solar tray dryer. Drying Technol. 20(6):1243-1271.

Yeh HM, Ho CD, Hou JZ. 1999. The improvement of collector efficiency in solar air heaters by simultaneously air flow over and under the absorber plate. Energy. 24(10):857-871

Yeh HM, Ho CD, Lin CY. 2000. Effect of collector aspect ratio on the collector efficiency of upward type baffled solar air heaters. Energy Conver Manage. 41(9):971-981

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1. Introduction

Solar energy is widely used to dry foods for short and long term preservation. For thousands of years, multiple cultures have harvested the sun's energy to preserve agricultural products (Fudholi and others, 2010). Historically this involved laying food in the sun to dry. This basic form of dehydration is still the most extensively used method of drying food in most tropical and sub-tropical locations (Tiris and others, 1994). Some of the problems associated with directly exposing food to the sun include vulnerability to vermin, contaminants, and weather. Direct exposure to the sun can also lead to over-drying, insufficient drying and discoloring due to UV radiation. Depending on the temperature and humidity, it can take weeks to completely dry foods. In order to successfully dry large quantities of food, large areas are needed to spread it out evenly in a single layer. The use of a solar heated dryer, instead of direct solar drying, can solve many of these problems while drying food more quickly and efficiently. Solar dryers are able to dry large quantities of food in a confined, protected space, thus increasing the product yield while preserving vital nutrients (Othman and others, 2006).

All solar dryers are comprised of two main parts: a dehydration chamber and a solar collector. The dehydration chamber is the area that contains the food, often on trays, and protects it from external contamination. The solar collector is made of an absorber that absorbs the sun's energy and converts it into heat, which is then transferred to the food by convective air flow. Many dryer designs have utilized some type of thermal storage material under the solar collector (Fudholi and others, 2010). This material absorbs some of the heat from the solar collector. When the solar collector can no longer absorb energy from the sun, the thermal storage material releases heat back into the dryer, continuing the drying process. In order to increase the convective air flow, chimneys have been added to many solar dryer designs.

Key factors contributing to a solar dryer's efficiency are temperature within the dryer, airflow rate through the dryer, and product load. El-Sebaii and others (2002) indicated the optimal temperature for drying common agricultural products was between 45.5-55.5°C. Yet, Leon and others (2002) noticed that increasing airflow increased drying efficiency even if air temperature dropped in the process. Karim and Hawlader (2006) showed that the air mass flow rate of 0.035 Kg/m^2s was optimal for their dryer design. Several studies have shown that product loading within the dehydration chamber can also have great impact on overall dryer efficiencies (Jain and Jain, 2004; Madhlopa and others, 2002).

Rowe and Steele (2004) developed a small-scale solar dryer, based on models for large-scale industrial processes, but using common, economical materials found in most hardware stores. This was designed for small-holdings farmers, who have limited monetary resources, allowing them to preserve crops for long-term storage. In 2009, Russon and others optimized the design of Rowe and Steele by increasing the number of trays within the dryer and increasing the height of the chimney used, while continuing to use simple materials. While the Russon dryer is very efficient, its lifespan is limited because the materials used to make it were not appropriate for long-term use. Another drawback to the modified design was its limited load capacity for commercial use.

The first objective of this research was to increase the size of Russon and others' (2009) solar dryer, which by default, would significantly increase its yield. In keeping with the goals from Russon and others' research, maintaining a low initial construction cost was pertinent for this study as well. The second objective was to take the newly constructed solar dryer and run performance tests on it.

2. Materials and Methods

2.1 Design of the Dryer

In order to maximize the efficiency of the solar dryer, a combination of indirect and direct solar heating was used in the design (figure 1). Indirect drying uses a solar collector to indirectly heat the dehydration chamber, while direct drying allows UV radiation from the sun directly into the dehydration chamber. The dimensions of the solar collector were 1.2 m by 2.4 m. The size of the dehydration chamber was 1.4 m (height) by 1.5 m (depth) by 1.2 m (width). The dryer was built, and the study conducted, in Provo, Utah, USA (40.2339°N, 111.6578°W, 1394 m elevation).

The dryer was faced directly south and the solar collector was tilted upwards at an angle of 30° in order to be most effective at collecting solar

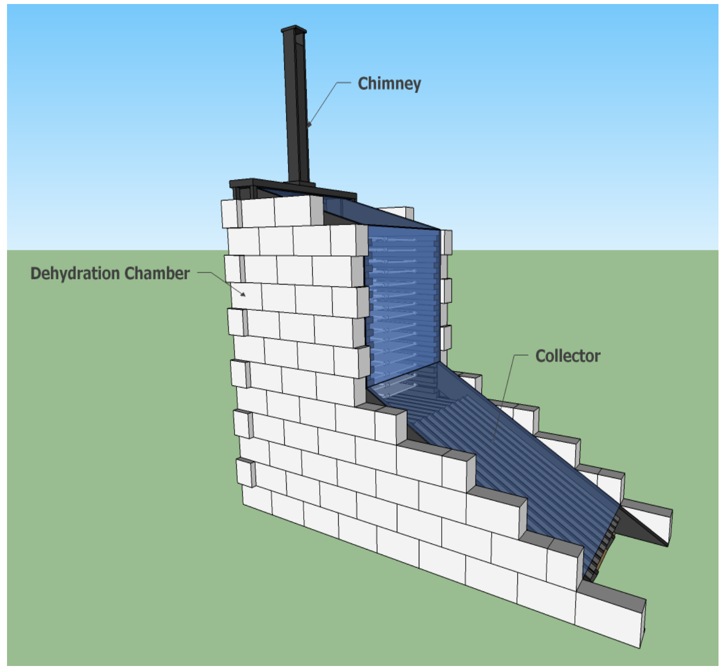

Figure 1 Designed solar dryer 3D view, major components labeled

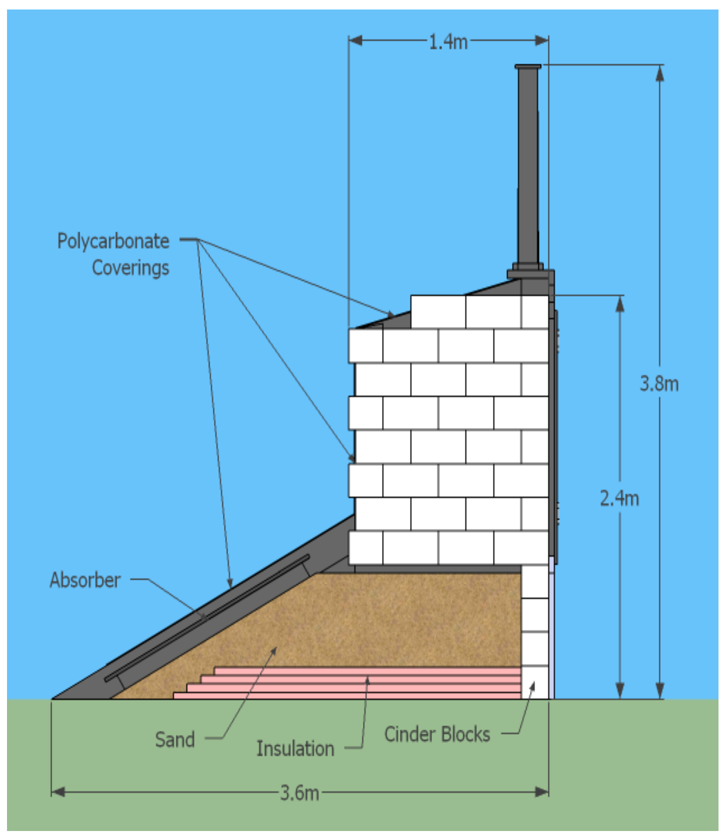

Figure 2 Cut-away side profile of solar dryer, showing dimensions and building materials

energy during the data collection season (June-August). The solar collector was comprised of an absorber made out of galvanized corrugated steel (panel was grade 80 full hard 29 gauge with 1 cm rib height, total coverage area of 1.86 m^2). Underneath the absorber was a 10 cm layer of washed, dried and screened sand acting as thermal storage (figure 2). Under the sand was a 3 cm layer of extruded polystyrene foam insulation to prevent heat from leaching to the ground. The absorber was made so that it could be positioned either 5 cm or 10 cm above the layer of sand. The absorber was covered by a 0.3 cm thick sheet of polycarbonate, which was 15 cm above the layer of sand.

The dehydration chamber was constructed of cinder block and wood and created an area that would hold fifteen 1.2m by 1.2m trays, spaced 5 cm apart, for holding product. The solar facing wall and roof were made of 0.3 cm thick sheets of polycarbonate in order to allow direct heating of the dehydration chamber (figure 2). Trays were made out of 1.25cm polyvinyl chloride (PVC) pipe fitted together in the shape of a square frame and were covered with food-grade industrial nylon netting (XN2335-48P, Industrial Netting, Minneapolis, Minnesota, USA). Each tray had 1.44 m^2 of drying area, for a total of 21.6 m^2 available in the dehydration chamber.

Two different chimney types were evaluated for the dryer. One was a simple box-type made from plywood. This chimney was attached to the top of the dryer using wire (figure 3). The other chimney was a collector-type, made from plywood and polycarbonate. The solar facing wall was made of polycarbonate and the opposite wall was painted black to create an absorber, allowing energy from the sun to heat the air in the chimney, with the intent of increasing convective airflow (figure 4). Each chimney had a cross sectional area of 0.01 m^2.

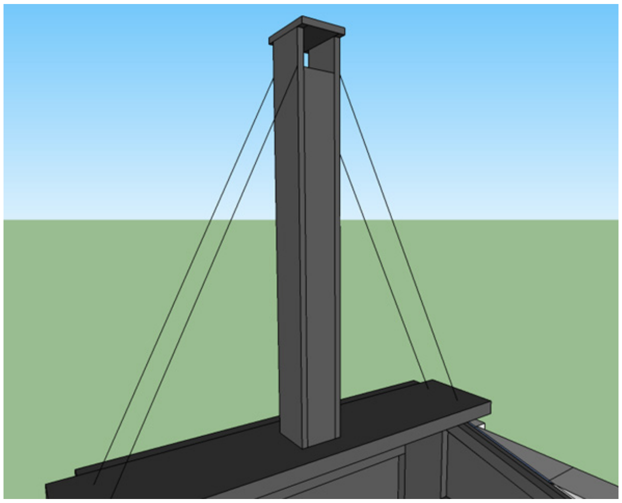

Figure 3 Box-type chimney

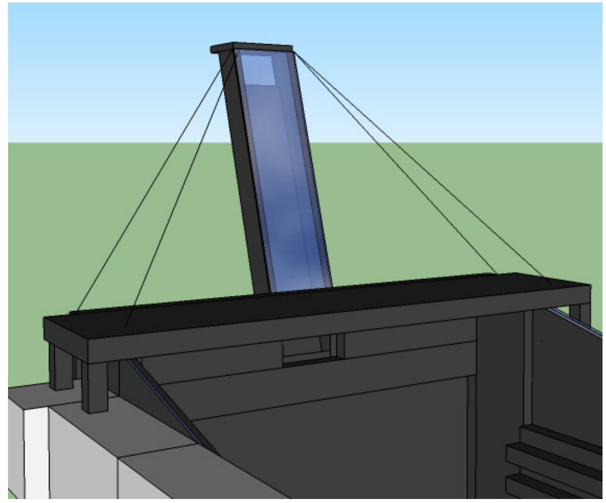

Figure 4 Collector-type chimney

2.2 Dryer Optimization

Performance testing of the dryer was determined by using a full factorial design. The factors of the design were: 1) two levels of product density load per tray, 2) three numbers of trays, 3) two absorber heights relative to sand layer, and 4) two types of chimneys. The two variables for product loading per tray were high (60% of the tray covered with potato slices) and low (40% of the tray covered with potato slices). The dryer was designed to hold a maximum of 15 trays; the variables in the number of trays tested were 5, 10, and 15. The absorber was either lowered to 5 cm above the sand or raised to 10 cm above the sand so that air could flow both over and under it. There were two types of chimneys tested, a regular box-type chimney and a solar collector-type chimney.

2.3 Sample Preparation

Russet potatoes were chosen as the test food for this project, because they were readily available and were used in previous dryer studies (Russon and others 2009). The potatoes were purchased at a local food market and sliced to a 3mm thickness using a rotary meat cutter. The potato slices were then cut to a diameter of 38mm using a sharpened cork borer. The potatoes were held at 2°C in a 1% (w/w) citric acid bath before drying to prevent browning.

2.4 Measurements

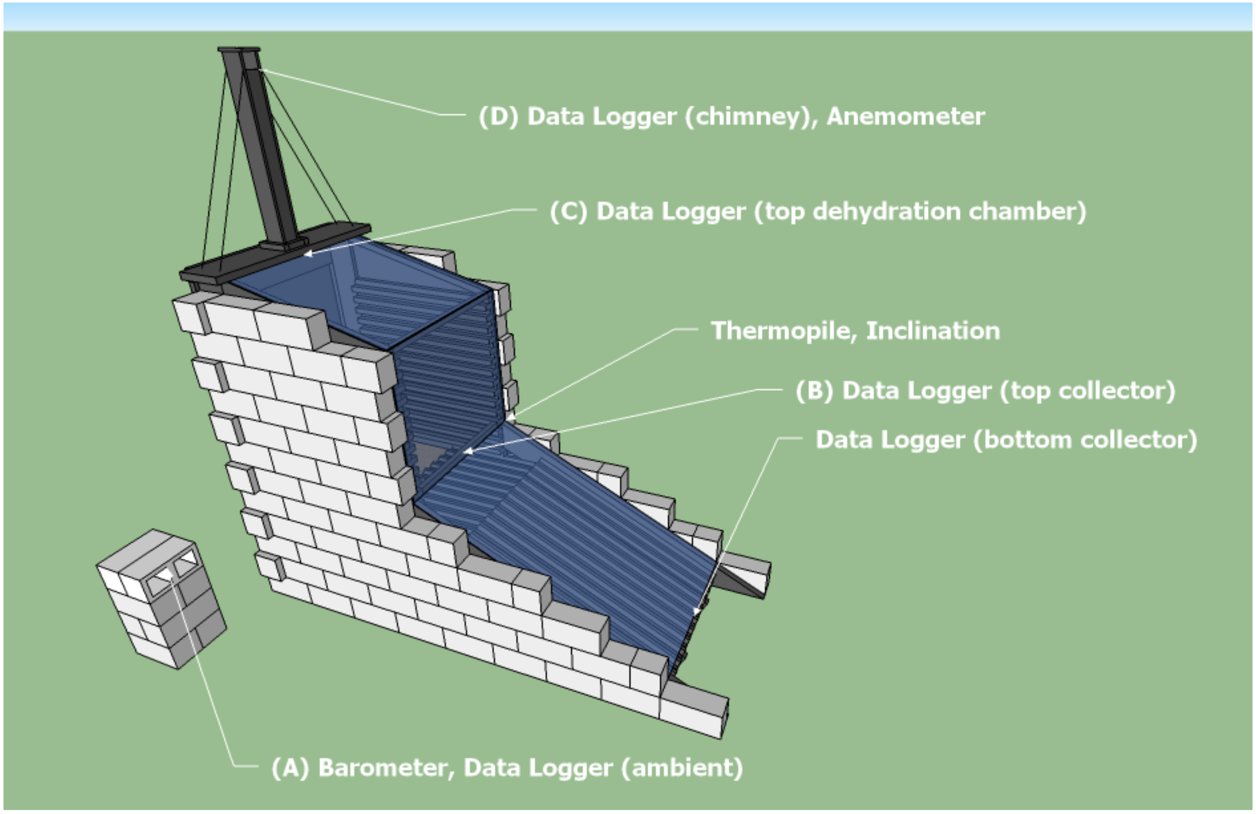

Figure 5 Placement of data recording instruments

2.4.1 Temperature and Relative Humidity

Data loggers (Lascar Electronics Ltd. data logger EL-USB-2-LCD, Pennsylvania, USA) were used to record temperature (°C) and relative humidity (%RH) at one minute intervals. These were placed centrally within the dryer at the bottom of the collector, top of the collector (B), top of the dehydration chamber (C) and the exit of the chimney (D). Each data logger was positioned out of direct sunlight. The ambient temperature (A) was measured by a data logger located to the rear of the dyer in a brick housing, painted white and elevated to a height of 1m as described by ASHRAE Standard 93-(2010). Refer to figure 5 for placement of all data loggers.

2.4.2 Air Flow

Air flow measurements were recorded every minute using an anemometer sensor located at the exit of the chimney; figure 5 point (D) (Venrier LabQuest 2 with attached anemometer sensor, Beaverton, Oregon, USA).

2.4.3 Sun Inclination

The inclination (angle, °) of the sun's rays incident to the polycarbonate covered surface of the collector was measured using a protractor mounted on the side of the dryer (figure 5). These measurements were taken at the start of each dryer trial run.

2.4.4 Solar Irradiance and Barometric Pressure

The barometric pressure (kPa) was recorded by a barometric pressure sensor attached to the Venrier LabQuest 2 data logger. This was converted to absolute pressure before being used for calculations. The barometric pressure sensor was located near the rear of the dryer in a brick housing (figure 5). The solar irradiance (I, W/m^2) was measured using a Texas Electronics TS-100 photovoltaic thermopile, see figure 5 for placement (Texas Electronics, Inc. Texas, USA).

2.5 Procedure for Testing a Treatment Combination

A total of 96 trials were conducted, 4 replicates of the 24 treatments. These were limited to hours when the sun was directly above the dryer (between 11am and 2pm), to maintain an appropriate angle of incidence as dictated in ASHRAE Standard 93-(2010). At the start of any given dryer run, potatoes were loaded onto trays, at either high or low density, according to the treatment plan. The trays were then placed into a controlled atmosphere room of 46°C, 90%RH until the potatoes reached a temperature of at least 38°C as measured by a hand held infrared thermometer (Oakton® TempTestr® IR, Oakton Instruments, Illinois, USA). This was done so that the potatoes would be closer to equilibrium with the dryer temperature once placed in the dryer. After the potatoes reached 38°C the trays were transferred to the dryer and the door of the dryer was closed. As soon as the temperature stabilized and remained constant for one minute, data recording began and continued for 30 minutes. Dryer runs were only recorded when the solar irradiance was greater than 800 W/m^2 as dictated in ASHRAE Standard 93-(2010).

2.6 Calculation of Efficiency

The calculation of collector efficiency (equation 1; Russon and others, 2009) is based on the energy gained by the air relative to the energy incident from the sun; where enthalpy across the collector (Δh, J/kg$_{\text{dry air}}$), mass flow rate (m, kg$_{\text{dry air}}$/s), solar irradiance (I, W/m^2) and collector aperture (Ap, m^2)

$$Efficiency_{collector} = \frac{Energy\ gained\ by\ air}{Energy\ incident\ from\ sun} = \frac{m \cdot \Delta h}{I \cdot Ap} \qquad \text{Equation 1}$$

The dehydrator efficiency (equation 2; Russon and others, 2009) is a measure of how well water is removed from the food or the percentage of water being removed from the food over time, as compared to the total amount of water the air could potentially hold. This is calculated determining the humidity ratio (w, kg$_{\text{moisture}}$/kg$_{\text{dry air}}$) of the ambient air, the air exiting the dryer, and the maximum possible humidity ratio corresponding to 100% relative humidity at the temperature measured at the top of the collector.

$$Efficiency_{dehydrator} = \frac{Water\ in\ air\ removed}{Water\ removed\ if\ air\ where\ saturated} = \frac{w_{final} - w_{ambient}}{w_{max\ possible} - w_{ambient}} \qquad \text{Equation 2}$$

The total efficiency (equation 3; Russon and others, 2009) of the dryer can be calculated by multiplying the efficiency ratios of the collector and the dehydration chambers together. This creates the following expression.

$$Efficiency_{total} = Efficiency_{collector} \cdot Efficiency_{dehydrator} \qquad \text{Equation 3}$$

2.7 Data Analysis

Statistical analysis was performed by using Statistical Analysis System software version 9.3 (SAS Institute, Inc., Cary, North Carolina, USA). Significant differences were defined as $p < 0.05$. Two different analyses were run: performance testing and efficiencies. Performance testing included independent variables for the ANOVA; chimney type, absorber setting, product loading and number of trays. The dependent variables, measured at various points as indicated in figure 5, were chimney air speed (D), temperature at the top of the collector (B), RH at the top of the collector (B), temperature at the top of the dehydration chamber (C), RH at the top of the dehydration chamber (C), temperature at the chimney outlet (D), RH at the chimney outlet (D), temperature B – temperature at A, and RH at D – RH at B. For the efficiency testing the independent variables for the ANOVA were chimney type, absorber setting, product loading and number of trays. The dependent variables were dehydrator efficiency, collector efficiency and total efficiency. The differences in irradiance between collection periods were adjusted for by using their values as a covariate.

3. Results and Discussion

3.1 Performance Testing

Performance testing was focused on air speeds, temperatures and humidity within the dryer during the 30 minute period following the stabilization of the temperature in the dehydration chamber. Raw values for each treatment are indicated in Table 10.

It was observed that the only variable that had an impact on the chimney air speed was chimney type, with a box-type chimney having air speeds 0.14 m/s faster than a collector-type chimney ($p = 0.0007$).

At the top of the collector (B) the greatest effect on temperature was an interaction between chimney type and absorber setting ($p = 0.0040$). When using a box-type chimney with a lowered absorber the collector temperature (B) was on average 4.9 °C colder than a box-type chimney and a raised absorber. Also using a box-type chimney with a lowered absorber resulted in an average temperature 3.3 °C colder than a collector-type chimney and a lowered absorber. Both of these effects may have been caused by increased airflow from the box-type chimney resulting in lower temperatures. The variable that had the greatest effect on relative humidity was an interaction between chimney type and absorber setting ($p = 0.0132$).

At the top of the dehydration chamber (C) the greatest effect on temperature was irradiance ($p = 0.0004$), the higher the irradiance the higher the temperature. The RH was most affected by the number of trays, with the highest RH values associated with 15 trays, next highest with 10 trays and the lowest with 5 trays ($p = 0.0080$). This effect was expected, with more moisture available to be removed with a higher number of loaded trays in the dryer.

At the chimney outlet (D) the most influential variable on temperature was chimney type. A collector-type chimney was found to be 9.54 °C hotter than the box-type chimney ($p < 0.0001$). Irradiance also contributed to chimney temperatures, with higher irradiance values associated with hotter temperatures.

3.2 Dehydrator Efficiency

Regardless of the variable, the overall efficiency of the dehydration chamber was low, averaging 7%. This low efficiency can be explained by one of the basic properties of air; as air gets hotter its capacity to hold moisture increases. Thus the only factor of the design that had any effect on dehydrator efficiency was number of trays (table 1). When number of trays in the dryer was increased from 5 to 15, the efficiency was 2.5% higher (p = 0.0007). This can be explained by noting that when the dryer had the higher number of trays in it the temperatures throughout the dryer were lower, reducing the maximum moisture that the air within the dryer could possibly remove. At the same time the product moisture available for vaporization was highest, making the ratio for dehydrator efficiency better.

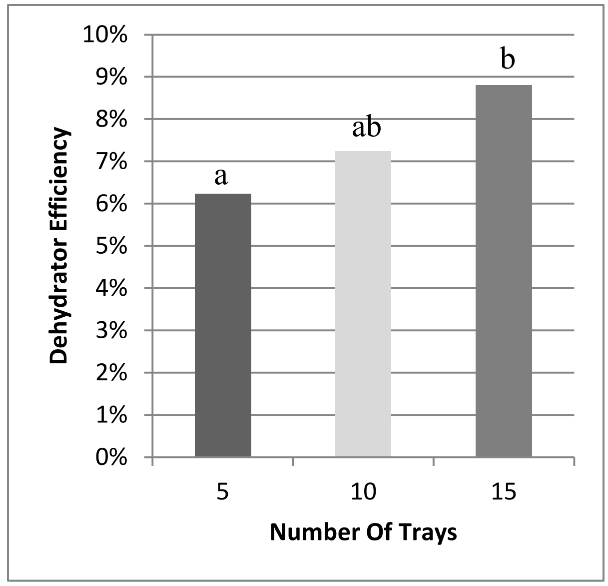

Table 1 Effect of number of trays on dehydrator efficiency. Letters denote significant differences.

3.3 Solar Collector Efficiency

It was observed that the type of chimney was a significant factor in collector efficiency (table 2). The box-type chimney was found to be 5.53% more efficient than the collector type (p = 0.0003). In our performance testing it was observed that the box-type chimney had higher chimney air speeds. Higher air speeds produce higher mass flow rates which increase collector efficiency (equation 1).

There were also two interactions with the solar collector that were significant. First was the interaction between the number of trays and the chimney type (table 3). There was no statistical difference between chimney types

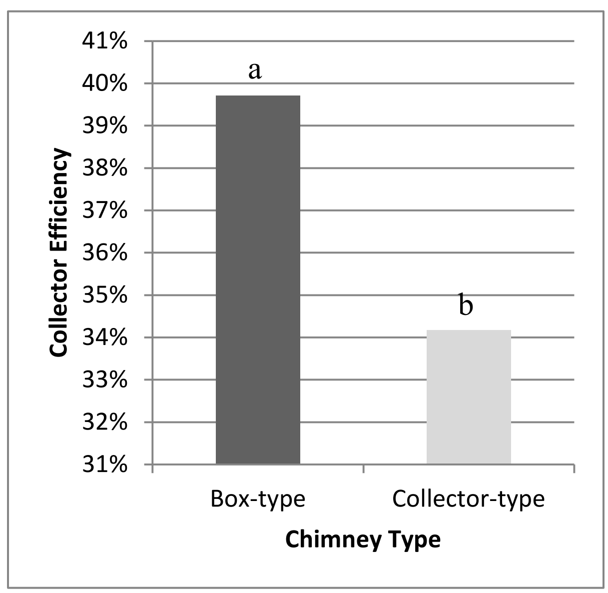

Table 2 Effect of chimney type on collector efficiency. Letters denote significant differences.

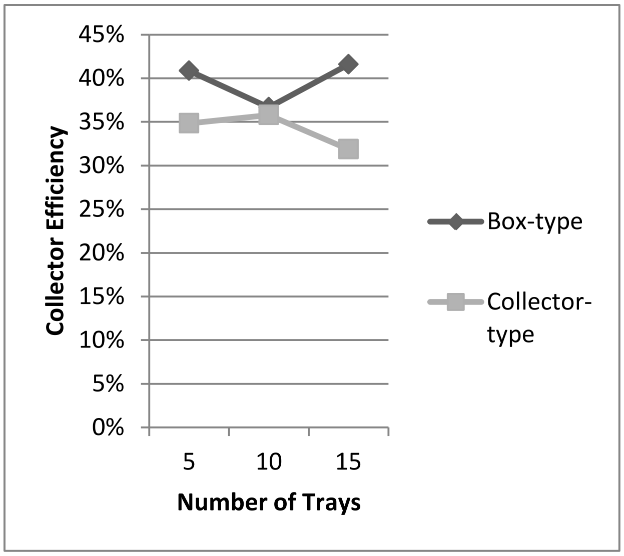

Table 3 Interaction between tray number and chimney type on collector efficiency

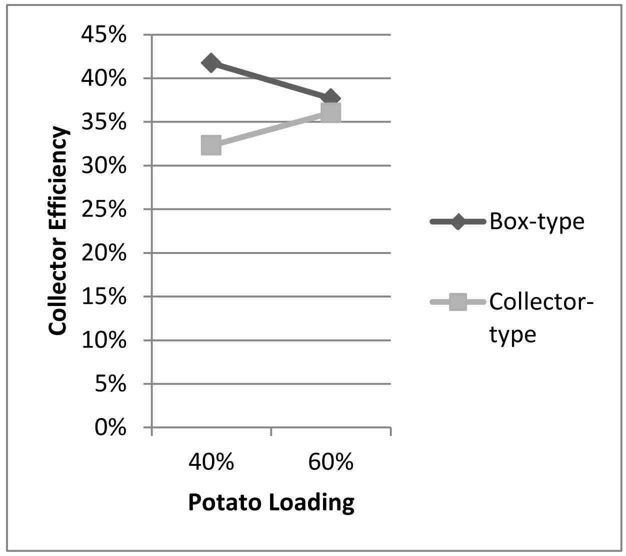

Table 4 Interaction between potato loading and chimney type on collector efficiency

when using 5 or 10 trays, but when using 15 trays the collector was 9.71% more efficient when using a box type chimney than when using a collector type chimney ($p = 0.0007$). This again shows that the box-type chimney was more efficient. The second interaction for collector efficiency was between potato loading density and chimney type (table 4). When using trays at 40 % capacity with potatoes, the collector was 9.41% more efficient when using a box type chimney than when using a collector type chimney ($p = 0.0001$). There was no real difference when the potato loading was 60%. It was apparent from looking at airspeeds during the course of the experiment that when using the box-type chimney the flow rates were faster. Flow rate has a very large impact on the collector efficiency, and will directly affect dryer temperatures (Montero and others, 2010).

3.4 Total Efficiency

Number of trays, chimney type and absorber configuration all had statistically significant impacts on total efficiency. When the number of trays was increased from 5 to 15 the total efficiency increased by 0.81% ($p = 0.0103$). With more trays there is more product to absorb heat lowering the temperature of the dryer. With a lower temperature the air actually holds less moisture, making the ratio of water removed to maximum amount removable better. Increasing the number of trays from 10 to 15 was also significant (p = 0.0408), showing an increase in efficiency of 0.69% (table 5).

A box-type chimney is 0.52% more efficient (total efficiency) than a collector-type chimney (p = 0.0273). As discussed before, the box-type chimney had better flow rates than the collector-type, hence the increase in efficiency (table 6).

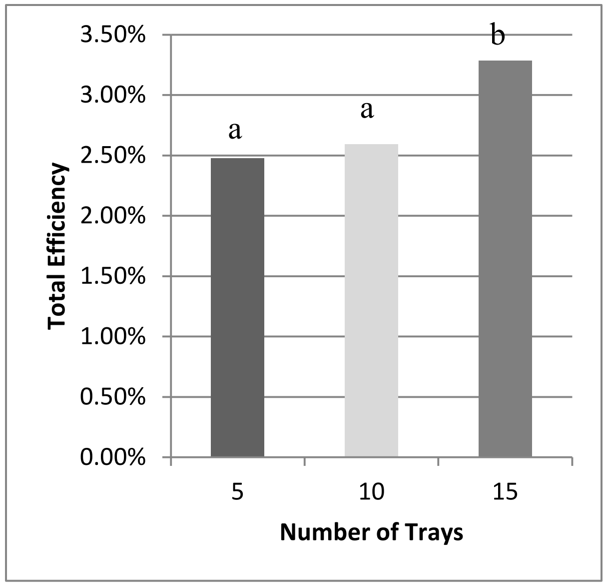

Table 5 Effect of number of trays on total efficiency. Letters denote significant differences.

A lowered absorber (5 cm from the sand) is 0.48% more efficient than a raised one (p = 0.0345). This could be due to the increased volume above the absorber, allowing for more heat

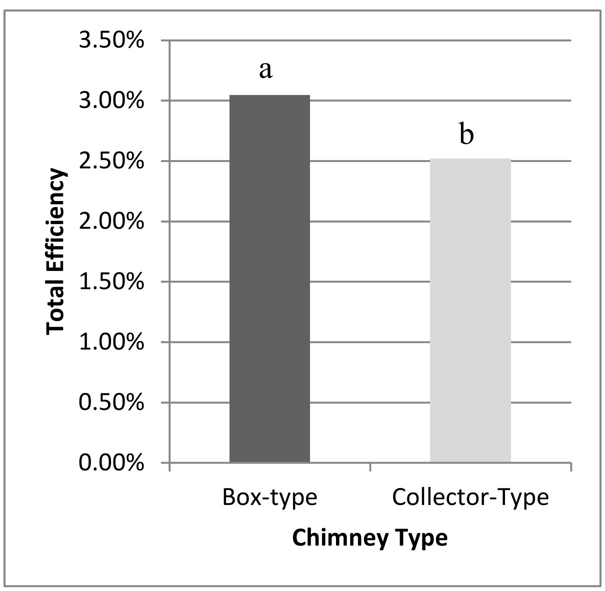

Table 6 Effect of chimney type on total efficiency. Letters denote significant differences.

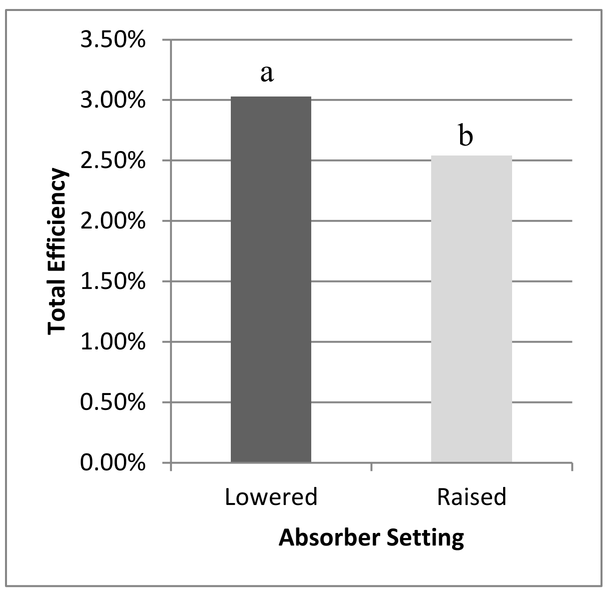

Table 7 Effect of absorber setting on total efficiency. Letters denote significant differences.

to transfer to the air and less to the sand below the absorber (table 7).

There were also two interactions that were significant when looking at total efficiency. The first was between the configuration of the absorber and the type of chimney (table 8). When the absorber was lowered the box-type chimney was 1.13% more efficient than the collector-type chimney (p = 0.0078). There was no difference between the two chimney types when the absorber was raised. This shows that the box-type chimney was more efficient when the absorber was lowered. With a box-type chimney having the absorber lowered was 1.17% more efficient than having it raised (p = 0.0069). Again the lowered absorber could increase the heat that is added to the air, increasing the efficiency of the dryer. Having the absorber lowered and a box-type chimney was 1.06% more efficient than having the collector raised with a collector-type chimney (p = 0.0201). A box-type chimney and a lowered absorber seemed to be the most efficient setting for the dryer.

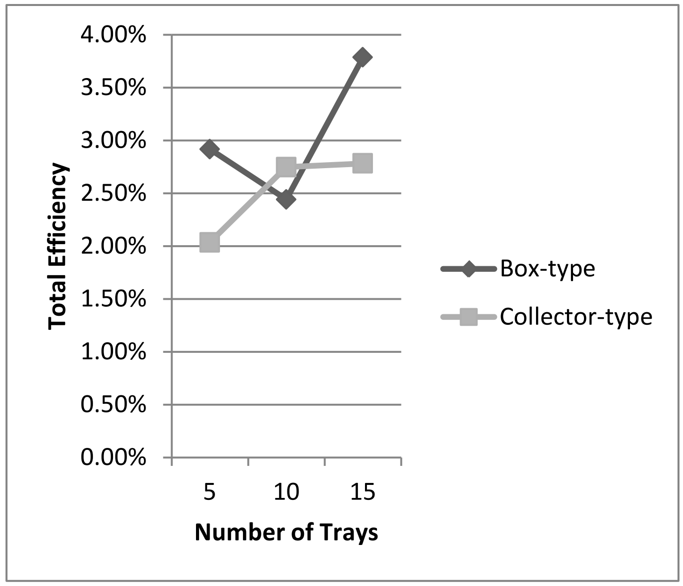

Table 8 Interaction between tray number and chimney type on total efficiency

The second interaction was between number of trays and type of chimney (table 9). When using a box-type chimney increasing the number of trays from 10 to 15 increased the efficiency by 1.34% (p = 0.0226). A box-type chimney with 15 trays was 1.75% more efficient than a collector-type chimney with 5 trays (p <0.0001). It was also shown that a box-type chimney with 15 trays was 1.75% more efficient than a collector-type chimney with 10 trays (p = 0.0474). All of these interactions support the conclusion that this dryer is more efficient when more loaded trays are in it, and the box-type chimney was more efficient than a collector-type chimney.

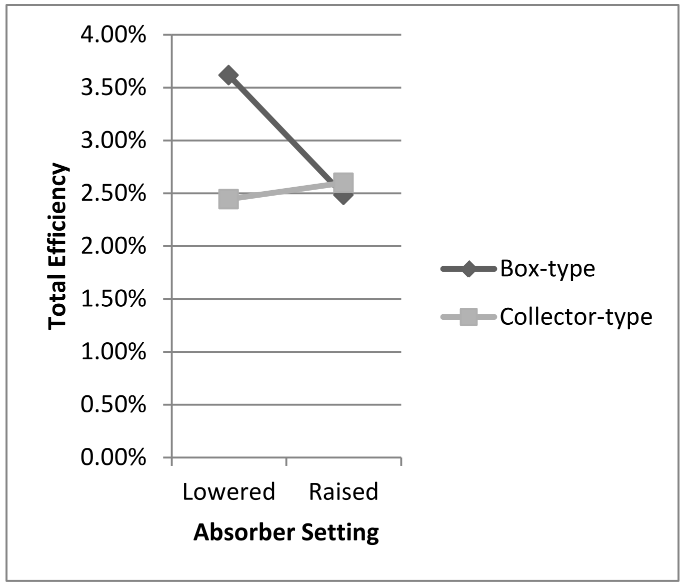

Table 9 Interaction between absorber setting and chimney type on total efficiency

4. Conclusions

Performance testing showed that chimney airspeeds were not affected greatly by modifying the design aspects of the dryer, with only a small increase occurring when using a box-type chimney. Overall the temperatures were mostly dependent on irradiance, but using a collector-type chimney generally resulted in higher temperatures throughout the dryer. The RH change across the dehydrator was most affected by the number of trays, but the chimney type did have an effect on the RH right at the chimney exit.

It was determined that the most efficient overall setting for this dryer was to have it loaded with 15 trays. Dryer efficiency due to the amount of potatoes per tray wasn't statistically significant, so it can be assumed that 60% loading works just as well as 40% loading. Lowering the absorber improved efficiencies more than having it raised. A box-type chimney was shown to be more efficient than the collector-type chimney.

Treatment							Ambient (A)		Top Collector (B)		Top Dehydrator (C)		Chimney (D)		Temerature increase across the collector	Increase in RH across the Dehydrator
Potato Loading	Tray Number	Absorber Setting	Chimney Type	Irradiance W/m^2	Pressure *kPa*	Chimney Air Speed *m/s*	Temp (A) °C	RH (A) %	Temp (B) °C	RH (B) %	Temp (C) °C	RH (C) %	Temp (D) °C	RH (D) %	B - A °C	D - B %
40%	5	Lowered	Box	882.77	85.98	1.53	22.22	21.90	59.37	6.42	49.78	21.17	46.50	22.45	37.15	16.03
40%	10	Lowered	Box	921.43	87.07	1.41	34.15	12.98	61.80	12.30	53.35	23.90	51.08	25.63	27.65	13.33
40%	15	Lowered	Box	897.33	86.11	1.58	21.85	33.13	60.10	7.73	49.61	28.21	46.28	31.68	38.25	23.95
60%	5	Lowered	Box	978.17	87.16	1.64	33.55	13.25	68.45	5.75	56.65	16.90	54.45	17.40	34.90	11.65
60%	10	Lowered	Box	857.54	85.63	1.52	20.13	22.12	56.85	7.22	49.65	21.82	46.15	23.47	36.72	16.25
60%	15	Lowered	Box	886.93	86.24	1.45	32.15	24.03	61.77	9.18	52.25	33.90	49.93	36.12	29.62	26.93
40%	5	Raised	Box	929.77	87.08	1.35	30.98	21.00	64.65	7.08	55.65	20.05	57.73	16.15	33.68	9.08
40%	10	Raised	Box	889.53	87.03	1.48	31.24	17.71	65.35	4.34	55.11	17.53	52.88	17.48	34.11	13.14
40%	15	Raised	Box	858.27	87.00	1.48	23.41	39.48	64.78	6.16	52.03	27.50	49.84	29.74	41.36	23.58
60%	5	Raised	Box	919.51	86.65	1.53	31.96	18.23	67.51	5.73	54.74	22.21	53.25	23.91	35.55	18.19
60%	10	Raised	Box	917.66	87.06	1.26	33.00	11.75	67.30	4.90	53.10	29.95	50.50	30.65	34.30	25.75
60%	15	Raised	Box	903.51	87.30	1.54	35.16	11.29	67.98	3.58	53.95	24.56	50.21	30.60	32.81	27.03
40%	5	Lowered	Collector	907.71	87.26	1.42	31.79	22.65	64.20	6.83	54.83	19.13	62.95	11.39	32.41	4.56
40%	10	Lowered	Collector	924.48	86.60	1.34	29.90	21.98	64.55	7.10	55.20	21.75	62.93	14.03	34.65	6.93
40%	15	Lowered	Collector	960.84	86.03	1.29	33.36	15.46	67.69	2.79	55.94	23.61	60.13	16.70	34.33	13.91
60%	5	Lowered	Collector	926.15	86.35	1.41	33.39	20.91	69.64	4.78	58.09	18.20	62.13	14.24	36.25	9.46
60%	10	Lowered	Collector	914.40	86.09	1.34	31.40	22.53	67.60	6.09	54.35	23.24	60.55	17.25	36.20	11.16
60%	15	Lowered	Collector	935.46	86.82	1.23	33.34	23.90	69.41	5.78	54.91	29.59	61.55	20.80	36.08	15.03
40%	5	Raised	Collector	936.76	86.21	1.37	35.47	20.17	70.38	4.78	59.23	18.48	60.72	17.08	34.92	12.30
40%	10	Raised	Collector	893.81	86.65	1.28	28.48	32.81	61.20	8.24	53.14	26.81	58.33	18.74	32.73	10.50
40%	15	Raised	Collector	910.58	85.83	1.33	29.73	28.33	64.42	5.70	54.18	26.38	60.97	17.03	34.68	11.33
60%	5	Raised	Collector	905.71	86.42	1.39	25.39	50.35	61.68	9.38	51.16	28.73	57.03	20.44	36.29	11.06
60%	10	Raised	Collector	865.86	86.27	1.44	28.27	17.14	65.49	4.66	51.01	25.74	59.55	15.39	37.21	10.73
60%	15	Raised	Collector	879.11	86.80	1.22	31.60	16.77	63.05	10.97	56.33	22.77	62.23	16.98	31.45	6.02

Table 10 Raw values for each dryer treatment, used for section 3.1 Performance testing

(Each value is the mean of 4 replicate dryer runs)

5. References

ASHRAE Standard 93-2010. Methods of testing to determine the thermal performance of solar collectors. Atlanta Georgia.

Ayensu A, Asiedu-Bondizie. 1986. Solar drying with convective self-flow and energy storage. Solar and Wind Technology. 3(4):273-279.

El-Sebaii AA, Aboul-Enein S, Ramadan MRI, El-Gohary HG. 2002. Experimental investigation of an indirect type natural convection solar dryer. Energ Convers Manage. 43: 2251-2266.

Fudholi A, Sopian K, Ruslan MH, Alghoul MA, Sulaiman MY. 2010. Review of solar dryers for agricultural and marine products. Renewable and Sustainable Energy Reviews. 14:1-30.

Jain D, and Jain RK. 2004. Performance evaluation of an inclined multi–pass solar air heater with in–built thermal storage on deep–bed drying application. Journal of Food Engineering. 65: 497–509.

Karim MA, Hawlader M. 2006. Performance investigation of flat plate, v-corrugated and finned air collectors. Energy. 31(4):452-470

Madhlopa A, Jones SA, Saka JDK. 2002. A solar air heater with composite absorber systems for food dehydration. Renew Energ. 27(1)27-37

Montero I, Blanco J, Miranda T, Rojas S, Celma AR. 2010. Design, construction and performance testing of a solar dryer for agroindustrial by-products. Energ Convers Manage. 51:1510-1521

Othman MYH, Sopian K, Yatmin B, Daud WRW. 2006. Development of advanced solar assisted drying systems. Renewable Energy. 31(5):703-709.

Russon J, Steele F. 2009. Optimization of a convective air flow solar food dryer. Int J of Food Eng. 5(1) Article 8

Tiris C, Ozbalta N, Tiris M, Dincer I. 1994. Experimental testing of a new solar dryer. Int J Energy Res. 16(4):483-491.

Appendices

Appendix A

Formulae

Table 1 Formulae used for efficiency calculations

Value	Definition	Units	Equation
t	Dry-bulb Temperature	°C	Direct Measurement
φ	RH	%	Direct Measurement
P	Pressure	kPa	Direct Measurement
W	Humidity Ratio;	$\frac{\text{kg moisture}}{\text{kg dry air}}$	Used Excel add-in to calculate *
Grains	Measurement of Moisture in air	$\frac{\text{Grains}}{\text{lb dry air}}$	$Grains = W \cdot 7000$ (only in American Units)
V	Specific Volume of Air;	m^3/kg	$V = \frac{287.055(273.15 + t_{db})(1 + 1.6078W_{end})}{P_{amb}(1 + W_{end})}$
v_f	Volumetric Flow Rate;	m^3/s	$v_f = Chimney\ Area\ \cdot Flow$
$\dot{m}$	Mass Flow Rate;	kg/s	$\dot{m} = \frac{v_f}{V} 60$
h_{tc}	Enthalpy of the air at top of collector;	J/kg	Used Excel add-in to calculate *
h_{amb}	Enthalpy of the ambient air;	J/kg	Used Excel add-in to calculate *
inclination	Inclination of the sun relative to collector	°	Direct Measurement
Ap	Aperture of the Collector;	m^2	$Ap = width \cdot length \cdot \sin(inclination)$
G	Irradiance;	W/m^2	Direct Measurement
$Eff_{collector}$	Efficiency of the Collector;	%	$Eff_{collector} = \frac{\dot{m} \cdot (h_{tc} - h_{amb})}{Ap \cdot G}$
$Eff_{dehydrator}$	Efficiency of the Dehydrator;	%	$Eff_{Dehydrator} = \frac{W_{end} - W_{amb}}{W_{max} - W_{amb}}$
Eff_{total}	Total efficiency of the Dryer;	%	$Eff_{total} = Eff_{collector} \cdot Eff_{dehydrator}$

*kW Psychometric Functions Excel add-in, kW Engineering, Oakland, California, USA

Appendix B

Calculation Procedure

Table 2 Calculation procedure flow chart

Dehydrator Efficiency		
Calculation	Raw value(s) needed	Pre-calculated value(s) needed
W_{end}	$t_{db,chimney}$ $RH_{chimney}$ P_{amb}	
W_{amb}	$t_{db,amb}$ RH_{amb} P_{amb}	
W_{max}	$t_{db,chimney}$ $RH_{100\%}$ P_{amb}	
$Grains$		W_{amb} W_{end} W_{max}
Collector Efficiency		
Calculation	Raw value(s) needed	Pre-calculated value(s) needed
h_{amb}	$t_{db,amb}$ RH_{amb} P_{amb}	
h_{tc}	$t_{db,tc}$ RH_{tc} P_{amb}	
V	$t_{db,chimney}$ P_{amb}	W_{end}
v_f	$Flow_{chimney}$	Chimney area = $0.01036m^2$
ṁ		v_f V
Ap	Inclination (°)	Area of Collector = $2.206m^2$
G	Irradiance	
Total Efficiency		
Calculation	Raw value(s) needed	Pre-calculated value(s) needed
Eff_{total}		$Eff_{collector}$ $Eff_{dehydrator}$

Appendix C

Placement of Data Recording Devises within the Dryer

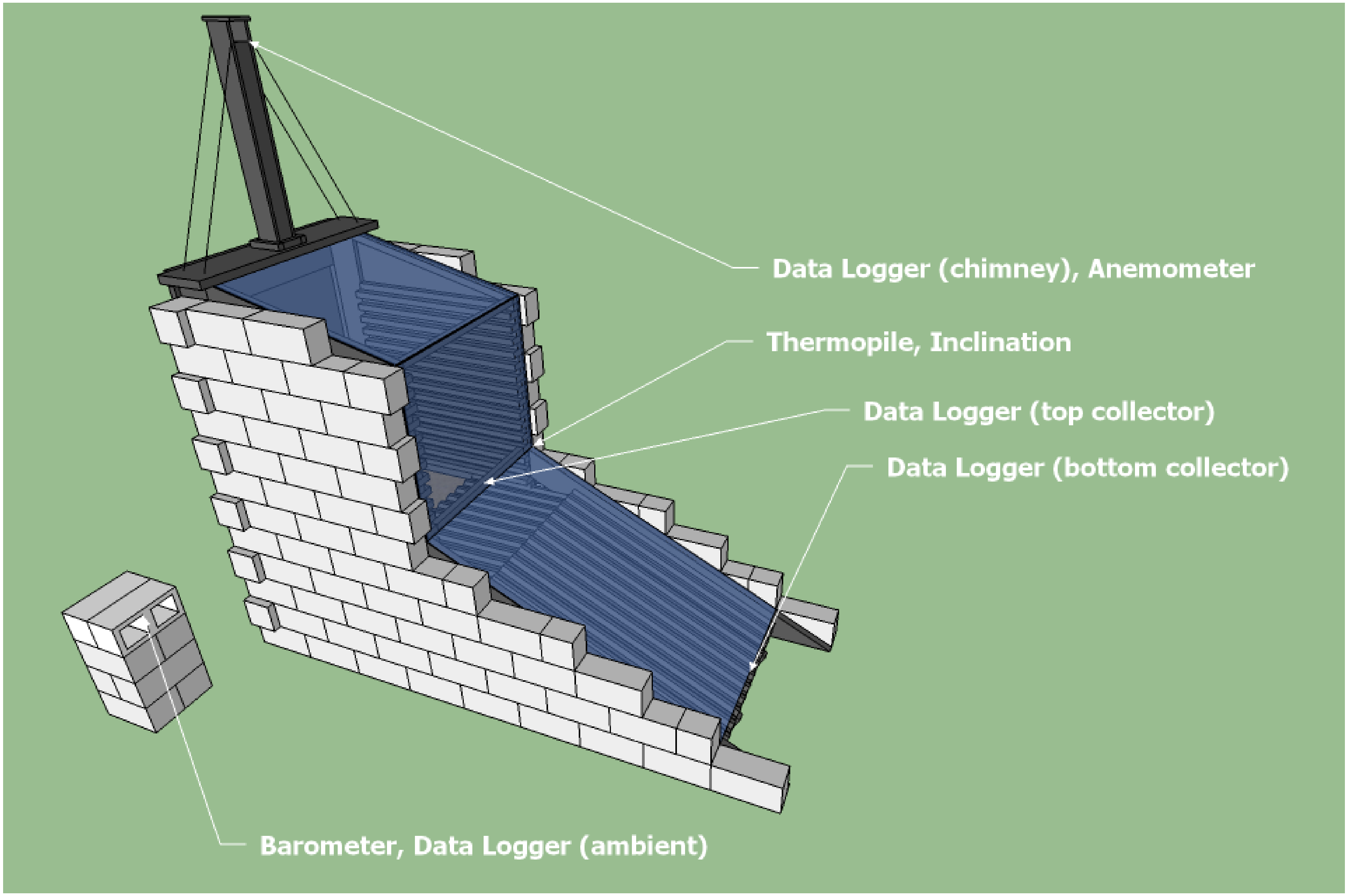

Figure 1 Dryer data recording placement

Appendix D

Data Tables

Total Efficiency Calculations

Table 3 Total efficiency raw data

	Design Factors						Efficiencies		
Order	**Potato Loading**	**Tray Number**	**Chimney Type**	**Collector Configuration**	**Date Complete**	***G***	**Dehydrator Efficiency**	**Collector Efficiency**	**Total Efficiency**
1	60%	5	box	raised	6/13/2012	954.312	6.58%	37.13%	2.44%
1b	60%	5	box	raised	6/13/2012	957.452	6.42%	36.22%	2.33%
2	40%	5	collector	lowered	6/14/2012	915.079	6.01%	33.14%	1.99%
2b	40%	5	collector	lowered	6/14/2012	938.036	6.72%	31.86%	2.14%
3	60%	10	collector	raised	6/18/2012	911.457	8.26%	44.77%	3.70%
3b	60%	10	collector	raised	6/18/2012	859.785	5.11%	40.65%	2.08%
4	40%	5	box	lowered	6/19/2012	817.519	9.59%	36.59%	3.51%
5	40%	10	box	raised	6/19/2012	929.670	4.77%	38.87%	1.85%
4b	40%	5	box	lowered	6/19/2012	952.968	5.03%	40.15%	2.02%
5b	40%	10	box	raised	6/19/2012	915.314	5.21%	35.99%	1.88%
6	40%	15	box	lowered	6/20/2012	949.400	12.24%	34.91%	4.27%
6b	40%	15	box	lowered	6/20/2012	934.416	6.77%	50.30%	3.41%
7	60%	15	box	lowered	6/21/2012	899.499	8.48%	51.05%	4.33%
7b	60%	10	box	lowered	6/21/2012	978.173	4.78%	43.32%	2.07%
8	60%	15	box	lowered	6/22/2012	944.789	12.02%	28.53%	3.43%
9	40%	10	collector	lowered	6/25/2012	955.014	6.69%	30.74%	2.06%
10	60%	15	box	raised	6/26/2012	956.123	11.55%	28.24%	3.26%
10b	60%	15	box	raised	6/26/2012	911.903	9.51%	28.31%	2.69%
11	40%	15	collector	lowered	6/27/2012	972.985	9.07%	17.54%	1.59%
11b	40%	15	collector	lowered	6/27/2012	967.373	5.83%	18.03%	1.05%
13	60%	10	box	raised	7/2/2012	917.659	8.64%	32.05%	2.77%
15	60%	5	collector	raised	7/6/2012	901.790	7.95%	37.76%	3.00%
15b	60%	5	collector	raised	7/6/2012	933.827	4.41%	40.47%	1.79%

	Design Factors						Efficiencies		
Order	Potato Loading	Tray Number	Chimney Type	Collector Configuration	Date Complete	*G*	Dehydrator Efficiency	Collector Efficiency	Total Efficiency
16	40%	15	box	raised	7/9/2012	876.430	8.63%	51.19%	4.42%
16b	40%	15	box	raised	7/9/2012	939.291	4.76%	49.52%	2.36%
17	60%	15	collector	lowered	7/10/2012	931.351	7.05%	30.28%	2.14%
17b	60%	15	collector	lowered	7/10/2012	1017.314	3.72%	26.49%	0.99%
18	60%	15	collector	raised	7/12/2012	863.962	13.67%	33.07%	4.52%
18b	60%	15	collector	raised	7/12/2012	928.233	9.73%	39.94%	3.89%
19	60%	10	collector	lowered	7/17/2012	923.195	7.60%	42.86%	3.26%
19b	60%	10	collector	lowered	7/17/2012	915.410	3.01%	31.56%	0.95%
20	40%	10	collector	raised	7/18/2012	922.129	9.10%	25.76%	2.34%
20b	40%	10	collector	raised	7/18/2012	932.574	3.42%	24.07%	0.82%
22	40%	15	collector	raised	7/25/2012	967.326	7.87%	29.20%	2.30%
22b	40%	15	collector	raised	7/25/2012	914.702	6.90%	30.39%	2.10%
23	60%	5	collector	lowered	7/26/2012	950.022	7.56%	31.06%	2.35%
24	40%	5	collector	raised	7/26/2012	965.924	6.16%	29.20%	1.80%
23b	60%	5	collector	lowered	7/26/2012	964.005	3.45%	29.28%	1.01%
24b	40%	5	collector	raised	7/26/2012	925.220	2.23%	30.55%	0.68%
25	40%	15	collector	lowered	8/2/2012	950.209	7.09%	34.11%	2.42%
25b	40%	15	collector	lowered	8/2/2012	952.810	4.51%	32.88%	1.48%
26	40%	5	box	raised	8/3/2012	877.169	6.77%	41.45%	2.81%
27	60%	5	collector	lowered	8/3/2012	938.807	3.89%	42.53%	1.65%
26b	40%	5	box	raised	8/3/2012	982.366	5.07%	31.74%	1.61%
27b	60%	5	collector	lowered	8/3/2012	851.777	3.86%	40.37%	1.56%
28	40%	5	collector	lowered	8/6/2012	838.379	5.98%	41.92%	2.51%
28b	40%	5	collector	lowered	8/6/2012	939.363	1.97%	36.73%	0.72%
30	40%	10	box	raised	8/7/2012	839.562	4.47%	25.37%	1.13%
29b	40%	5	collector	raised	8/7/2012	919.137	6.45%	35.83%	2.31%
30b	40%	10	box	raised	8/7/2012	873.588	4.85%	32.98%	1.60%

	Design Factors						Efficiencies		
Order	Potato Loading	Tray Number	Chimney Type	Collector Configuration	Date Complete	*G*	Dehydrator Efficiency	Collector Efficiency	Total Efficiency
31	60%	15	box	raised	8/8/2012	839.815	6.96%	36.76%	2.56%
31b	60%	15	box	raised	8/8/2012	906.180	4.82%	36.87%	1.78%
35	60%	5	box	raised	8/17/2012	905.478	9.13%	43.12%	3.94%
35b	60%	5	box	raised	8/17/2012	860.813	4.44%	42.85%	1.90%
36	60%	10	box	lowered	8/20/2012	829.209	12.12%	33.73%	4.09%
36b	60%	10	box	lowered	8/20/2012	843.911	6.77%	44.01%	2.98%
37	60%	10	collector	lowered	8/21/2012	903.275	9.14%	37.36%	3.42%
37b	60%	10	collector	lowered	8/21/2012	915.723	6.05%	37.67%	2.28%
38	60%	15	box	lowered	8/24/2012	855.350	15.29%	47.95%	7.33%
38b	60%	15	box	lowered	8/24/2012	860.663	10.68%	42.77%	4.57%
39	60%	15	collector	lowered	8/25/2012	883.131	11.29%	35.55%	4.01%
39b	60%	15	collector	lowered	8/25/2012	910.030	9.37%	37.32%	3.50%
40	40%	10	collector	raised	9/7/2012	802.261	15.86%	37.68%	5.97%
41	60%	5	collector	raised	9/7/2012	876.371	10.94%	43.24%	4.73%
40b	40%	10	collector	raised	9/7/2012	918.268	7.36%	40.72%	3.00%
41b	60%	5	collector	raised	9/7/2012	910.867	8.01%	35.98%	2.88%
42b	40%	10	collector	lowered	9/8/2012	893.943	7.69%	44.94%	3.46%
43	60%	10	collector	raised	9/14/2012	805.921	9.12%	34.18%	3.12%
43b	60%	10	collector	raised	9/14/2012	886.294	5.47%	34.59%	1.89%
44	40%	15	box	raised	9/18/2012	802.779	11.54%	42.41%	4.89%
44b	40%	15	box	raised	9/18/2012	814.595	7.17%	44.66%	3.20%
45b	60%	15	collector	raised	9/21/2012	845.138	7.80%	36.66%	2.86%
46b	40%	5	box	lowered	9/22/2012	877.813	7.38%	49.26%	3.63%
47	40%	15	box	lowered	9/28/2012	815.734	13.01%	55.45%	7.21%
47b	40%	15	box	lowered	9/28/2012	889.768	8.63%	48.38%	4.17%
48b	40%	15	collector	raised	9/29/2012	849.700	7.99%	32.82%	2.62%

Data was excluded from analysis if the irradiance values were less than 800 W/m^2.

Dehydrator Efficiency

Table 4 Dehydrator efficiency raw data

W end			W amb			W max			Moisture Grains			
$t_{chimney}$	$RH_{chimney}$	W_{end}	t_{amb}	RH_{amb}	W_{amb}	t_{tc}	$RH_{100\%}$	W_{max}	end	amb	max	Dehydrator Efficiency
133.50	18.05%	0.0226	88.70	9.95%	0.0033	153.50	100%	0.2966	158.29	23.25	2076.19	6.58%
130.40	18.75%	0.0216	92.39	8.85%	0.0033	152.70	100%	0.2878	151.08	23.19	2014.89	6.42%
138.92	12.15%	0.0174	85.91	20.35%	0.0062	140.90	100%	0.1915	121.67	43.71	1340.82	6.01%
141.53	11.65%	0.0178	87.62	19.25%	0.0062	138.83	100%	0.1786	124.75	43.62	1250.13	6.72%
132.35	19.45%	0.0237	87.40	11.20%	0.0036	148.28	100%	0.2475	166.23	25.20	1732.73	8.26%
138.56	13.15%	0.0187	90.71	11.00%	0.0039	153.14	100%	0.2933	130.96	27.44	2053.00	5.11%
106.70	28.85%	0.0171	73.22	26.70%	0.0054	128.21	100%	0.1273	119.89	38.06	891.37	9.59%
122.18	17.80%	0.0164	76.10	20.70%	0.0046	148.55	100%	0.2508	114.56	32.41	1755.57	4.77%
122.36	21.35%	0.0198	81.50	15.65%	0.0042	155.03	100%	0.3148	138.44	29.16	2203.66	5.03%
128.48	17.05%	0.0186	85.10	15.20%	0.0045	151.25	100%	0.2743	130.20	31.79	1919.90	5.21%
111.65	33.30%	0.0229	71.87	18.95%	0.0037	135.59	100%	0.1607	160.13	25.57	1124.95	12.24%
119.39	20.60%	0.0174	79.07	13.35%	0.0033	144.05	100%	0.2120	121.76	22.79	1484.19	6.77%
120.56	27.45%	0.0243	84.02	17.20%	0.0050	146.66	100%	0.2325	169.78	34.66	1627.61	8.48%
130.01	17.40%	0.0197	92.39	13.25%	0.0049	155.21	100%	0.3127	137.61	34.63	2189.18	4.78%
123.80	24.75%	0.0239	93.74	7.50%	0.0029	138.65	100%	0.1777	167.54	20.49	1244.08	12.02%
144.41	15.50%	0.0257	94.10	16.05%	0.0063	153.68	100%	0.2957	179.83	44.31	2069.56	6.69%
113.45	36.45%	0.0264	92.75	5.70%	0.0022	144.05	100%	0.2124	185.07	15.05	1486.96	11.55%
116.78	32.20%	0.0256	97.16	3.80%	0.0016	149.27	100%	0.2534	178.97	11.45	1773.55	9.51%
133.61	18.00%	0.0225	86.90	12.10%	0.0038	143.78	100%	0.2104	157.82	26.65	1472.72	9.07%
138.20	13.60%	0.0191	90.59	10.60%	0.0037	150.71	100%	0.2664	133.36	26.16	1864.45	5.83%
122.90	30.65%	0.0290	91.40	11.75%	0.0043	153.14	100%	0.2907	203.08	29.78	2034.69	8.64%
121.46	29.00%	0.0263	91.94	14.15%	0.0052	138.74	100%	0.1774	184.01	36.55	1241.49	12.24%
126.41	22.25%	0.0229	95.00	11.80%	0.0048	147.74	100%	0.2401	160.62	33.44	1680.64	7.72%
127.76	24.40%	0.0263	73.40	61.50%	0.0126	139.91	100%	0.1848	184.21	88.40	1293.82	7.95%

W end			W amb			W max			Moisture Grains			
$t_{chimney}$	$RH_{chimney}$	W_{end}	t_{amb}	RH_{amb}	W_{amb}	t_{tc}	$RH_{100\%}$	W_{max}	end	amb	max	Dehydrator Efficiency
137.30	18.25%	0.0253	75.29	58.60%	0.0128	153.50	100%	0.2950	176.84	89.65	2064.71	4.41%
124.07	34.20%	0.0335	73.40	60.60%	0.0123	149.90	100%	0.2572	234.38	86.41	1800.59	8.63%
135.68	23.05%	0.0306	83.30	41.15%	0.0116	162.68	100%	0.4106	214.05	81.02	2874.39	4.76%
144.95	22.50%	0.0384	94.55	24.80%	0.0099	162.77	100%	0.4136	268.90	69.58	2895.38	7.05%
153.41	16.25%	0.0339	100.49	18.95%	0.0091	174.38	100%	0.6778	237.60	63.50	4744.81	3.72%
140.00	21.20%	0.0316	93.25	14.67%	0.0056	141.89	100%	0.1959	221.30	39.32	1370.97	13.67%
151.52	14.90%	0.0296	94.33	15.49%	0.0061	148.73	100%	0.2469	206.88	42.90	1728.05	9.73%
135.23	21.60%	0.0285	85.73	26.65%	0.0081	151.61	100%	0.2754	199.15	56.86	1928.06	7.60%
135.95	12.80%	0.0169	88.16	25.50%	0.0084	153.05	100%	0.2894	117.97	58.73	2026.04	3.01%
139.64	17.60%	0.0258	86.99	20.95%	0.0066	144.95	100%	0.2176	180.63	46.27	1522.89	9.10%
146.39	9.50%	0.0163	90.50	20.85%	0.0074	151.07	100%	0.2687	113.98	51.47	1881.13	3.42%
141.98	18.15%	0.0288	89.51	27.55%	0.0096	148.82	100%	0.2535	201.52	67.14	1774.65	7.87%
144.23	18.00%	0.0304	91.67	25.95%	0.0097	154.31	100%	0.3098	212.79	67.88	2168.64	6.90%
140.18	19.35%	0.0295	89.24	27.80%	0.0097	150.62	100%	0.2723	206.56	67.56	1906.24	7.56%
140.09	16.60%	0.0251	93.92	22.35%	0.0090	150.44	100%	0.2713	175.94	62.90	1899.22	6.16%
149.27	13.00%	0.0248	96.53	21.30%	0.0093	164.39	100%	0.4596	173.63	64.96	3217.29	3.45%
153.86	9.90%	0.0210	99.50	17.60%	0.0084	169.70	100%	0.5756	147.14	58.64	4029.41	2.23%
144.50	19.65%	0.0338	93.29	23.50%	0.0093	157.73	100%	0.3553	236.65	65.03	2487.09	7.09%
144.59	15.55%	0.0266	97.43	15.65%	0.0070	163.13	100%	0.4418	186.49	49.21	3092.69	4.51%
125.96	19.70%	0.0200	83.39	27.10%	0.0077	140.81	100%	0.1901	140.10	53.63	1331.01	6.77%
134.42	14.80%	0.0188	87.62	20.40%	0.0066	155.84	100%	0.3203	131.46	46.06	2242.35	3.89%
145.85	12.60%	0.0215	92.12	14.90%	0.0055	155.93	100%	0.3210	150.64	38.64	2246.65	5.07%
151.43	9.80%	0.0191	95.00	14.15%	0.0057	158.54	100%	0.3533	134.03	40.10	2472.88	3.86%
146.39	13.70%	0.0236	89.42	27.35%	0.0093	149.09	100%	0.2491	165.53	65.17	1743.92	5.98%
154.40	8.05%	0.0167	93.92	23.65%	0.0092	161.42	100%	0.3898	117.12	64.74	2728.45	1.97%
120.29	18.35%	0.0157	92.39	21.10%	0.0079	140.09	100%	0.1837	110.06	55.09	1286.02	4.47%
129.92	24.75%	0.0281	94.10	20.55%	0.0081	155.93	100%	0.3180	196.56	56.55	2225.82	6.45%

W end			W amb			W max			Moisture Grains			
$t_{chimney}$	$RH_{chimney}$	W_{end}	t_{amb}	RH_{amb}	W_{amb}	t_{tc}	$RH_{100\%}$	W_{max}	end	amb	max	Dehydrator Efficiency
137.75	16.70%	0.0231	99.32	13.85%	0.0064	158.63	100%	0.3510	161.63	44.54	2457.29	4.85%
126.59	30.00%	0.0313	93.56	19.55%	0.0076	158.36	100%	0.3490	219.38	52.97	2442.99	6.96%
132.71	23.75%	0.0291	97.70	16.10%	0.0071	165.74	100%	0.4642	203.55	49.41	3249.42	4.82%
117.77	36.45%	0.0301	85.82	30.65%	0.0094	147.02	100%	0.2358	210.73	65.97	1650.81	9.13%
129.74	22.40%	0.0255	91.22	23.45%	0.0085	160.88	100%	0.3910	178.68	59.84	2736.96	4.44%
103.01	26.45%	0.0142	58.10	25.45%	0.0031	118.58	100%	0.0945	99.21	21.60	661.81	12.12%
121.64	16.50%	0.0151	62.60	23.70%	0.0034	137.75	100%	0.1769	105.86	23.66	1238.07	6.77%
139.55	21.30%	0.0323	87.35	21.65%	0.0071	151.43	100%	0.2827	226.01	49.66	1979.00	9.14%
153.23	13.30%	0.0282	92.84	16.30%	0.0063	158.63	100%	0.3685	197.61	44.34	2579.67	6.05%
117.50	46.10%	0.0386	86.00	34.00%	0.0106	140.90	100%	0.1935	270.01	74.31	1354.26	15.29%
124.34	37.50%	0.0379	89.87	30.60%	0.0108	149.99	100%	0.2644	265.17	75.62	1851.04	10.68%
134.06	24.40%	0.0317	83.93	27.20%	0.0079	144.50	100%	0.2184	221.66	55.37	1528.78	11.29%
138.74	20.05%	0.0293	89.06	24.65%	0.0084	146.12	100%	0.2310	205.09	59.14	1616.78	9.37%
120.65	29.65%	0.0266	73.40	49.55%	0.0102	124.61	100%	0.1136	186.40	71.72	794.95	15.86%
135.41	21.25%	0.0285	77.00	45.55%	0.0106	137.66	100%	0.1738	199.30	74.37	1216.77	10.94%
141.26	18.20%	0.0283	82.13	39.90%	0.0110	148.01	100%	0.2466	198.36	77.04	1726.42	7.36%
138.11	17.85%	0.0255	85.10	35.75%	0.0109	140.99	100%	0.1943	178.82	76.03	1360.18	8.01%
146.12	12.55%	0.0219	77.54	27.90%	0.0066	142.70	100%	0.2056	153.24	46.05	1439.53	7.69%
137.93	16.50%	0.0234	74.21	24.60%	0.0052	142.61	100%	0.2048	163.75	36.24	1433.82	9.12%
147.92	12.45%	0.0227	79.25	21.75%	0.0054	155.48	100%	0.3218	159.07	37.87	2252.80	5.47%
107.87	35.00%	0.0217	67.28	29.80%	0.0050	133.16	100%	0.1501	151.98	34.76	1050.62	11.54%
119.21	26.70%	0.0226	72.59	26.35%	0.0052	148.64	100%	0.2485	158.42	36.39	1739.49	7.17%
140.54	14.85%	0.0226	79.07	20.15%	0.0050	145.85	100%	0.2309	158.53	35.11	1616.50	7.80%
118.04	17.15%	0.0141	61.25	23.35%	0.0032	133.34	100%	0.1518	98.83	22.09	1062.50	7.38%
111.29	40.30%	0.0280	65.30	51.50%	0.0081	135.14	100%	0.1612	196.10	56.65	1128.43	13.01%
118.85	32.50%	0.0280	69.08	48.70%	0.0087	145.94	100%	0.2319	195.93	61.10	1623.37	8.63%
139.01	14.95%	0.0219	75.38	31.50%	0.0070	140.72	100%	0.1936	153.05	48.66	1355.18	7.99%

Collector Efficiency

Table 5 Collector efficiency raw data

Mass Flow Rate Calculation				Enthalpy			Gross Collector Area				
$W_{chimney}$	V	v_f	$\dot{m}$	h_{amb}	h_{tc}	Δh	Area of Collector	Inclination	Ap	G	Collector Efficiency
0.0226	1.144	0.0166	0.0145	33305.5	87117.7	53812.1	2.206	94	2.201	954.31	37.13%
0.0216	1.141	0.0174	0.0153	39163.3	89185.1	50021.7	2.206	94	2.201	957.45	36.22%
0.0174	1.116	0.0147	0.0132	38327.0	88895.2	50568.2	2.206	95	2.198	915.08	33.14%
0.0178	1.112	0.0161	0.0144	38872.8	84350.4	45477.5	2.206	95	2.198	938.04	31.86%
0.0237	1.138	0.0177	0.0156	35469.3	93077.9	57608.6	2.206	95	2.198	911.46	44.77%
0.0187	1.142	0.0150	0.0132	36994.8	95382.0	58387.2	2.206	95	2.198	859.78	40.65%
0.0171	1.101	0.0149	0.0136	27930.7	76486.2	48555.5	2.206	94	2.201	817.52	36.59%
0.0164	1.137	0.0161	0.0141	27564.3	83857.4	56293.1	2.206	94	2.201	929.67	38.87%
0.0198	1.148	0.0140	0.0122	29861.2	98971.3	69110.1	2.206	94	2.201	952.97	40.15%
0.0186	1.139	0.0159	0.0139	32487.1	84573.9	52086.8	2.206	94	2.201	915.31	35.99%
0.0229	1.111	0.0167	0.0150	24966.6	73532.2	48565.6	2.206	94	2.201	949.40	34.91%
0.0174	1.118	0.0177	0.0158	28102.7	93400.0	65297.2	2.206	94	2.201	934.42	50.30%
0.0243	1.130	0.0176	0.0156	35262.2	100106.4	64844.2	2.206	94	2.201	899.50	51.05%
0.0197	1.138	0.0170	0.0149	38465.8	100927.3	62461.5	2.206	94	2.201	978.17	43.32%
0.0239	1.117	0.0139	0.0124	40356.1	88068.4	47712.2	2.206	94	2.201	944.79	28.53%
0.0257	1.139	0.0130	0.0114	40334.8	97205.9	56871.0	2.206	93	2.203	955.01	30.74%
0.0264	1.126	0.0169	0.0150	37816.8	77466.9	39650.1	2.206	93	2.203	956.12	28.24%
0.0256	1.132	0.0179	0.0158	38404.7	74321.1	35916.3	2.206	93	2.203	911.90	28.31%
0.0225	1.122	0.0125	0.0112	32725.4	66389.7	33664.3	2.206	93	2.203	972.98	17.54%
0.0191	1.130	0.0133	0.0117	34092.9	66835.1	32742.2	2.206	93	2.203	967.37	18.03%
0.0290	1.142	0.0131	0.0114	36892.6	93598.8	56706.2	2.206	92	2.205	917.66	32.05%
0.0263	1.118	0.0133	0.0119	35079.1	98407.4	63328.3	2.206	91	2.206	901.79	37.76%
0.0253	1.141	0.0144	0.0126	33985.0	100055.7	66070.7	2.206	91	2.206	933.83	40.47%
0.0335	1.133	0.0149	0.0132	29105.1	104239.5	75134.4	2.206	91	2.206	876.43	51.19%
0.0306	1.152	0.0159	0.0138	33765.0	108334.2	74569.2	2.206	91	2.206	939.29	49.52%

Mass Flow Rate Calculation				Enthalpy			Gross Collector Area				
$W_{chimney}$	V	v_f	$\dot{m}$	h_{amb}	h_{tc}	Δh	**Area of Collector**	**Inclination**	Ap	G	**Collector Efficiency**
0.0384	1.160	0.0117	0.0101	41462.6	103093.8	61631.3	2.206	91	2.206	931.35	30.28%
0.0339	1.177	0.0122	0.0104	42353.6	99569.2	57215.5	2.206	91	2.206	1017.31	26.49%
0.0316	1.118	0.0112	0.0100	56932.3	119915.7	62983.4	2.206	90	2.206	863.96	33.07%
0.0296	1.128	0.0124	0.0110	56846.3	131030.4	74184.1	2.206	90	2.206	928.23	39.94%
0.0285	1.139	0.0144	0.0126	38108.2	107150.2	69042.0	2.206	89	2.206	923.19	42.86%
0.0169	1.133	0.0130	0.0114	39066.7	94810.5	55743.8	2.206	89	2.206	915.41	31.56%
0.0258	1.121	0.0123	0.0110	37066.5	84715.7	47649.2	2.206	89	2.206	922.13	25.76%
0.0163	1.126	0.0122	0.0109	39373.5	84971.6	45598.1	2.206	89	2.206	932.57	24.07%
0.0288	1.147	0.0135	0.0117	44571.7	97551.8	52980.2	2.206	87	2.203	967.33	29.20%
0.0304	1.161	0.0133	0.0114	44601.5	98234.1	53632.7	2.206	87	2.203	914.70	30.39%
0.0295	1.157	0.0121	0.0105	42120.5	104172.9	62052.4	2.206	87	2.203	950.02	31.06%
0.0251	1.156	0.0124	0.0108	43088.5	100863.3	57774.8	2.206	87	2.203	965.92	29.20%
0.0248	1.182	0.0132	0.0111	43985.7	99838.8	55853.1	2.206	87	2.203	964.00	29.28%
0.0210	1.189	0.0143	0.0120	44759.0	96549.6	51790.6	2.206	87	2.203	925.22	30.55%
0.0338	1.178	0.0140	0.0119	45215.4	105206.7	59991.4	2.206	85	2.198	950.21	34.11%
0.0266	1.189	0.0137	0.0115	43616.4	103457.6	59841.2	2.206	85	2.198	952.81	32.88%
0.0200	1.114	0.0164	0.0147	37255.1	91642.6	54387.5	2.206	85	2.198	877.17	41.45%
0.0188	1.139	0.0173	0.0152	36246.7	94041.8	57795.2	2.206	85	2.198	938.81	42.53%
0.0215	1.140	0.0115	0.0101	36571.1	104515.0	67943.9	2.206	85	2.198	982.37	31.74%
0.0191	1.143	0.0160	0.0140	38304.4	92349.3	54044.9	2.206	84	2.194	851.78	40.37%
0.0236	1.122	0.0143	0.0127	43115.9	103625.7	60509.8	2.206	84	2.194	838.38	41.92%
0.0167	1.139	0.0136	0.0119	43651.1	107146.6	63495.5	2.206	84	2.194	939.36	36.73%
0.0157	1.101	0.0135	0.0122	45498.5	83713.4	38214.9	2.206	84	2.194	839.56	25.37%
0.0281	1.138	0.0159	0.0139	45834.0	97683.4	51849.4	2.206	84	2.194	919.14	35.83%
0.0231	1.139	0.0159	0.0139	47209.0	92615.2	45406.2	2.206	84	2.194	873.59	32.98%
0.0313	1.147	0.0138	0.0120	44820.5	101184.7	56364.2	2.206	84	2.194	839.82	36.76%
0.0291	1.157	0.0150	0.0130	45396.4	101843.8	56447.4	2.206	84	2.194	906.18	36.87%

Mass Flow Rate Calculation				Enthalpy			Gross Collector Area				
$W_{chimney}$	V	v_f	$\dot{m}$	h_{amb}	h_{tc}	Δh	Area of Collector	Inclination	Ap	G	Collector Efficiency
0.0301	1.136	0.0141	0.0124	42292.0	111058.3	68766.3	2.206	82	2.185	905.48	43.12%
0.0255	1.160	0.0151	0.0130	42457.9	104271.3	61813.3	2.206	82	2.185	860.81	42.85%
0.0142	1.093	0.0134	0.0122	18041.4	67861.0	49819.7	2.206	81	2.179	829.21	33.73%
0.0151	1.131	0.0164	0.0145	20070.7	75990.9	55920.2	2.206	81	2.179	843.91	44.01%
0.0323	1.167	0.0138	0.0118	38303.5	100591.5	62287.9	2.206	81	2.179	903.27	37.36%
0.0282	1.178	0.0144	0.0122	39395.8	100852.9	61457.1	2.206	81	2.179	915.72	37.67%
0.0386	1.139	0.0168	0.0147	44994.6	105439.9	60445.3	2.206	80	2.172	855.35	47.95%
0.0379	1.155	0.0144	0.0125	44475.1	108642.8	64167.7	2.206	80	2.172	860.66	42.77%
0.0317	1.140	0.0132	0.0115	37874.8	96996.3	59121.5	2.206	80	2.172	883.13	35.55%
0.0293	1.142	0.0139	0.0122	40988.5	101694.0	60705.5	2.206	80	2.172	910.03	37.32%
0.0266	1.102	0.0132	0.0119	38579.2	93191.2	54612.0	2.206	78	2.158	802.26	37.68%
0.0285	1.127	0.0146	0.0130	39296.7	102376.6	63079.9	2.206	78	2.158	876.37	43.24%
0.0283	1.145	0.0154	0.0135	42857.6	102725.2	59867.7	2.206	78	2.158	918.27	40.72%
0.0255	1.132	0.0151	0.0134	46022.3	98930.3	52908.0	2.206	78	2.158	910.87	35.98%
0.0219	1.132	0.0148	0.0131	31808.9	98022.4	66213.4	2.206	78	2.158	893.94	44.94%
0.0234	1.132	0.0134	0.0118	28999.6	79127.6	50128.0	2.206	77	2.149	805.92	34.18%
0.0227	1.155	0.0136	0.0118	31263.7	87332.9	56069.2	2.206	77	2.149	886.29	34.59%
0.0217	1.116	0.0153	0.0137	26140.0	79379.8	53239.8	2.206	77	2.149	802.78	42.41%
0.0226	1.131	0.0153	0.0136	28002.5	85691.3	57688.8	2.206	77	2.149	814.60	44.66%
0.0226	1.145	0.0144	0.0126	32119.7	84849.1	52729.4	2.206	76	2.140	845.14	36.66%
0.0141	1.116	0.0185	0.0166	19279.6	74964.3	55684.6	2.206	76	2.140	877.81	49.26%
0.0280	1.129	0.0162	0.0143	27529.8	94866.2	67336.3	2.206	75	2.131	815.73	55.45%
0.0280	1.150	0.0148	0.0129	28912.6	100086.2	71173.6	2.206	75	2.131	889.77	48.38%
0.0219	1.133	0.0145	0.0128	33859.1	80285.8	46426.8	2.206	75	2.131	849.70	32.82%

Data was excluded from analysis if the irradiance values were less than 800 W/m^2

Appendix E

Solar Dryer Construction and Use Manual

Solar Dryer Construction and Use Manual

Version 1.0 2012

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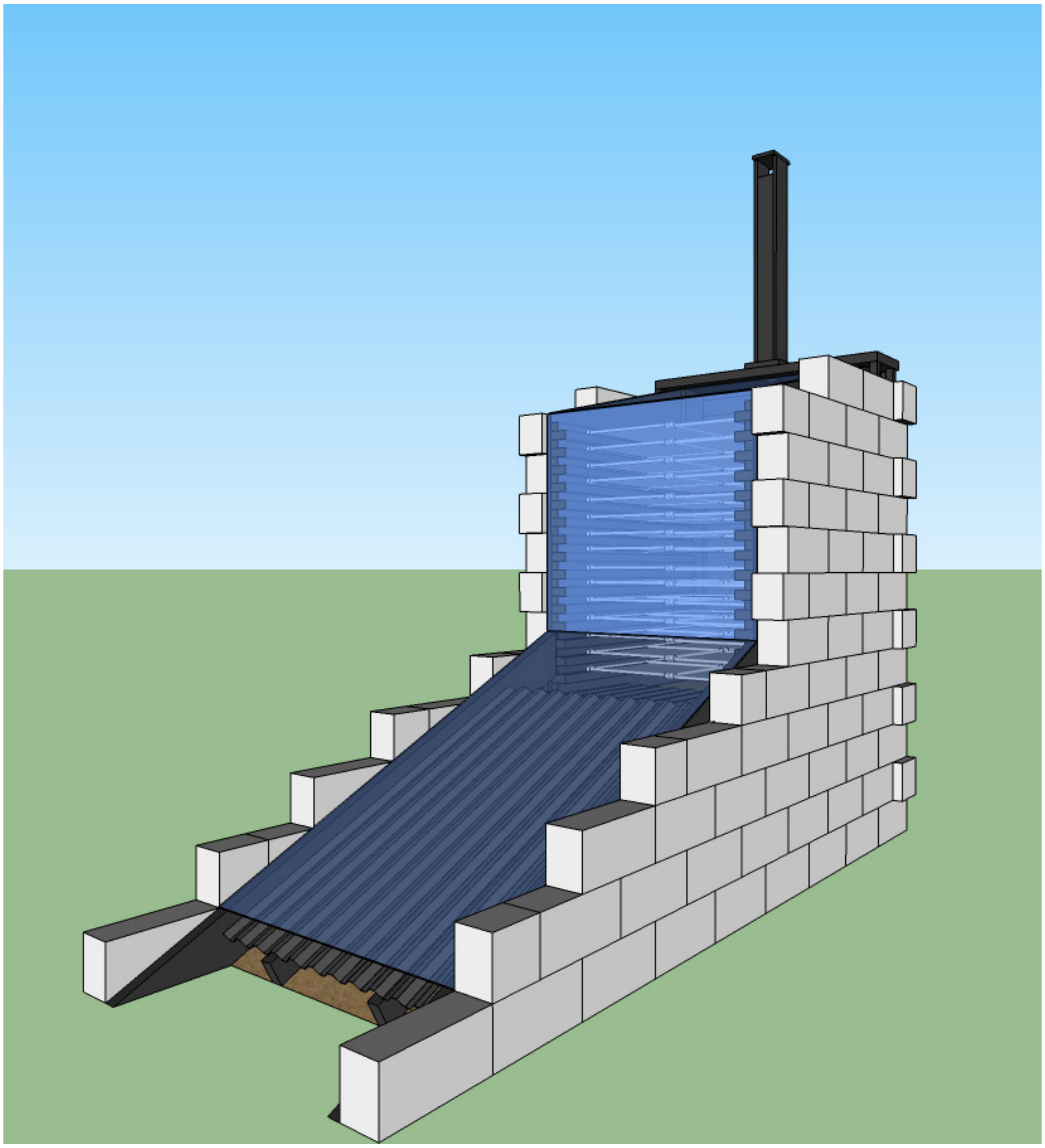

Figure 1 Solar dryer

Introduction

This dryer design has about $22m^2$ of drying space. As such it is best used by a larger scale farmer, or small community. A single family may have trouble filling the dryer. One of the major goals of this dryer design was to keep the cost low for this dryer, and having a community pitch in to buy the materials is a good way to accomplish this.

As stated before keeping the cost of the dryer low was a major goal of this design. The materials used in this design were chosen because they were either cheap or easily accessible throughout the world. Bricks or masonry blocks are fairly cheap as well as the wood used. Corrugated steel was used as the collector because of how readily available it is in most areas of the world. The most expensive part of this dryer is the polycarbonate that is needed. One way around this cost is to make the roof of the dehydration chamber out of corrugated steel (painted black). Though it will be much less efficient clear plastic can be substituted for the polycarbonate. Depending on the area and availability another option is Lexan. It is more expensive, but allows heat into the dryer better, and is more resistant to the weather. Whether using polycarbonate, Lexan or clear plastic, if it turns opaque or yellows it should be replaced.

Some carpentry and masonry skills are needed to successfully build this dryer. However, they are in no way advanced enough to prevent most anyone from building this dryer.

Materials List

Table 1 Material List (US and Metric Measurements)

Quantity	Description	Dimensions	Metric Measurements
	Brick		
104	Full cinder blocks	8" x 8" x 16"	20cm x 20cm x 40cm
20	Half blocks	8" x 8" x 8"	20cm x 20cm x 20cm
	Wood		
3	Plywood sheet	4' x 8' x 3/4"	2.4m x 1.2m x 19mm
24	Treated Pine Lumber	2" x 4" x 8'	5cm x 10cm x 2.4m
20	Treated Pine Lumber	2" x 2" x 8'	5cm x 5cm x 2.4m
6	Treated Pine Lumber	2" x 8" x 8'	5cm x 20cm x 2.4m
	Polycarbonate (if this size cannot be found, get pieces that cover the same area)		
1	Lexan, Plexiglas or similar material	4' x 8' x 1/8"	2.4m x 1.2m x 3mm
2	Lexan, Plexiglas or similar material	4' x 5' x 1/8"	1.5m x 1.2m x 3mm
	Miscellaneous		
2.5kg	Screws	3.5" long	90mm long
2	Heavy duty hinges	4"	10cm
1	Handle	4"	10cm
-	10 gauge wire	20'	6m
8	Eye Hooks	#4	
1	Latch/Lock		
8 Tubes	Silicone Sealant		
100	Lag Bolts/Screws	5" long	127mm long
-	Paint, Flat Black	1 Gallon	3.75 Liter
-	Straw (enough to cover dimensions)	4' x 12' x 4"	1.2m x 3.6m x 10cm
-	Sand or other fine material	0.5-1 yards	0.5-1 $meters^3$
1	Corrugated Tin	4' x 8'	2.4m x 1.2m
	PVC Shelves		
15	4 Way Joints	All fittings for tube in 0.5 inch diameter	All fittings for tube in 12.7mm diameter
60	T Joints		
60	Corners		
180	Tubes	18.25"x0.5'	463.5cm x 12.7mm
255	Zip Ties	4" long	10cm long
-	Nylon Mesh Netting (1 cm openings)	50'x4'	1.2m x 15.25m

Procedure for Assembly

Site Selection

Select a flat area of ground approximately 2.5m by 6m (8 ft by 20 ft). As far as is possible this needs to be an area with no shade (Figure 1). Trees and structures may be present at the rear of the dryer, so long as they do not shade the front of the dryer. The goal is to have as much sun on the front of the dryer as is possible. The general rule is to place the front of the dryer towards the hemisphere that the sun is in the most during the year. More specifically the direction the front of the dryer will face is dependent on the latitude of the location the dryer is being built. If the dryer is built north of 15° N it should be faced south. If it is built between 15° N and 15° S it should be faced towards the east so that the sun will rise over the front of the dryer and set toward the rear. A dryer built south of 15° S should face north. The closer to the equator this dryer is built the longer the period of time it will be effective for during the year.

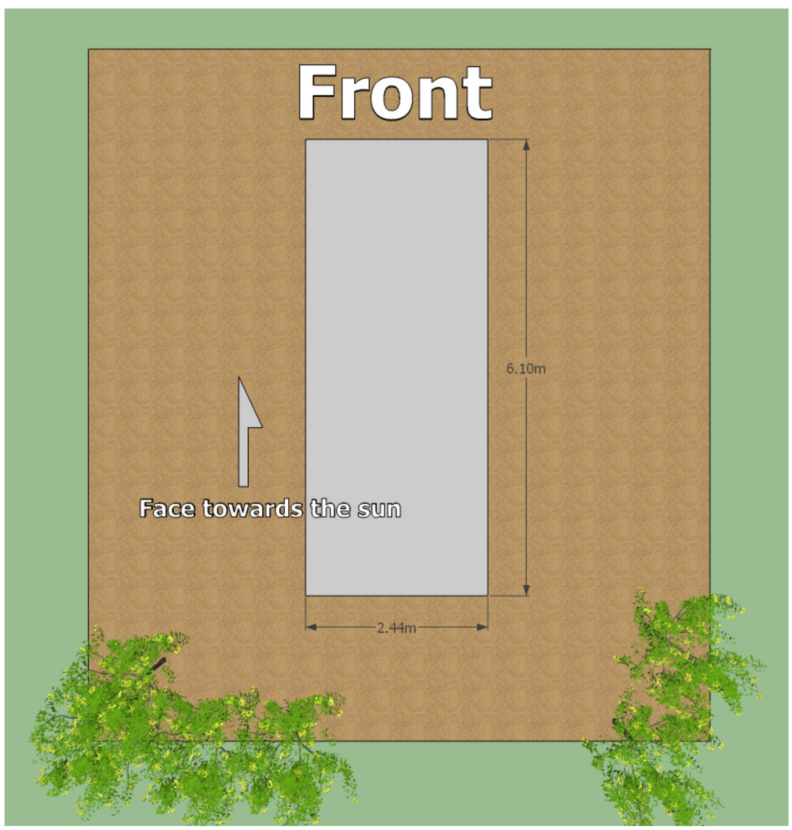

Figure 2 Site selection

Construction

The dryer is broken into 2 main sections: the collector and the drying chamber. The collector is the long flat area of the dryer that contains the black corrugated tin, and this section creates the heat that dries the food. The other section is the dehydration chamber, which is the tall section with a chimney on top. It contains the shelves that hold the trays for the product that needs to be dried (Figure 2).

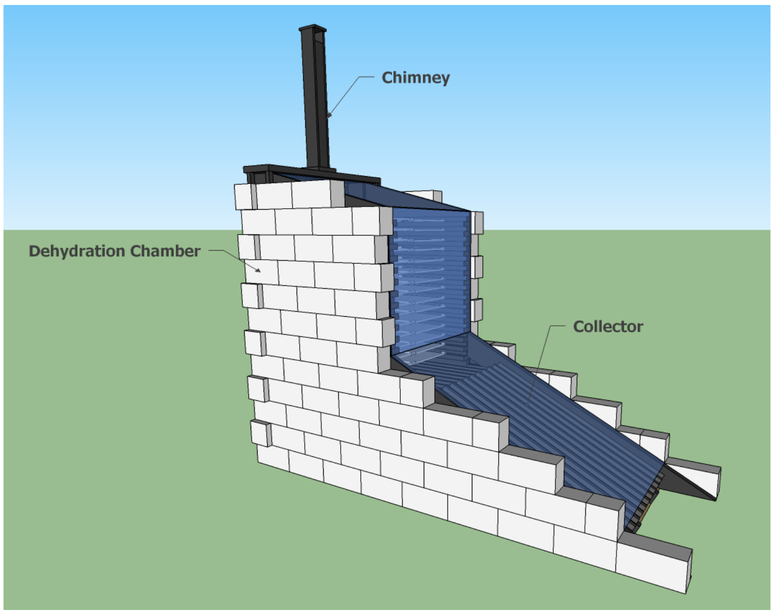

Figure 3 Dryer design components

1. Square off an area that is 1.52m by 3.66m. Start the walls by building a foundation (cement or some other sturdy material). This may be the entire area, but to save costs a foundation under the three walls will suffice (Figure 3).

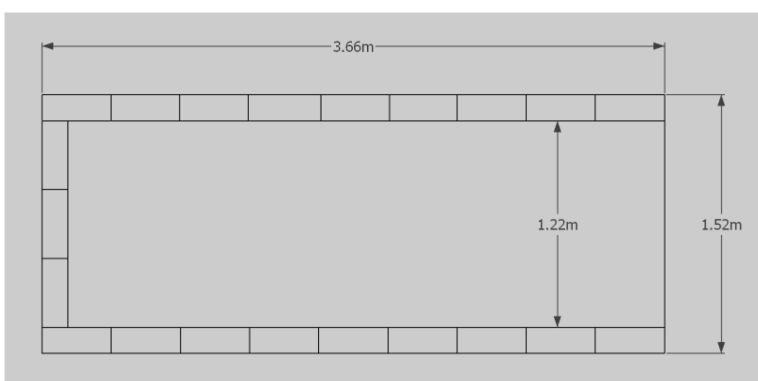

Figure 4 Foundation diagram

2. Once a sturdy foundation is in place, start building the two walls with the cinder blocks leaving a 1.2 m gap in between the walls (Figure 3). If possible use mortar to cement the blocks in place. The first four courses of brick (if using 20cm x 20cm x 40cm blocks (8"x8"x16")) will encompass the two sides and the rear of the dryer, while the front of the dryer is left without any brick. Refer to Figures 4 and 5 for how to set the blocks.

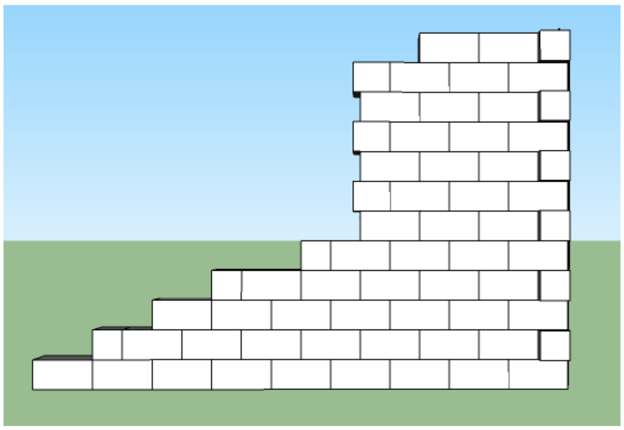

Figure 5 Outside wall

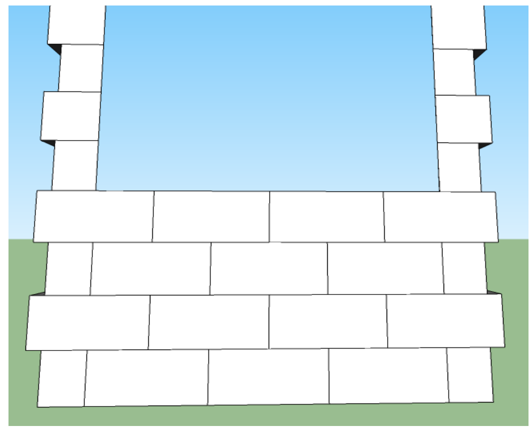

Figure 6 End wall

3. Line the inside of each of wall with a sheet of plywood (1.2m x 2.4m). This will give the shelves mounting support, in addition to the block, adding strength to the drying chamber (Figure 6).

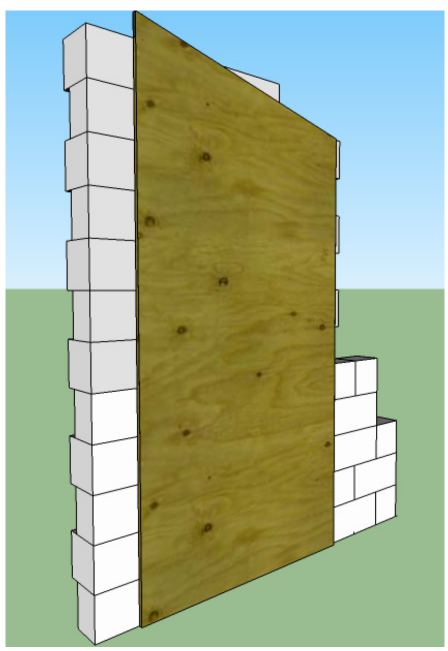

Figure 7 Inside wall plywood lining

4. Cut the following:

    28 5cm x 5cm x 1.2m boards

    30 5cm x 10cm x 1.2m boards

5. The shelves for the trays are built by bolting a 2x2 onto the wall of the dryer and then attaching a 2x4 on top of it, continuing up each interior wall of the dryer. To bolt the 2x2 to the wall a masonry bit or self-tapping screws and drill are required. Bolt each shelf support to the plywood and brick with 3 bolts/screws. The first shelf support is a 2x4, bolted in 0.71m from the ground. The bottom of the first shelf should be even with the top of the bricks in the back (Figure 7). On top of that lay a 2x4 on its side and screw it onto the on you just bolted into the wall (Figure 8). Continue up the wall bolting a 2x2 onto the wall (Figure 9) and securing a 2x4 on top of it until there are 15 shelves. The front of the shelf is aligned to the front of the drying chamber. This creates an anchor for the polycarbonate that will be installed later.

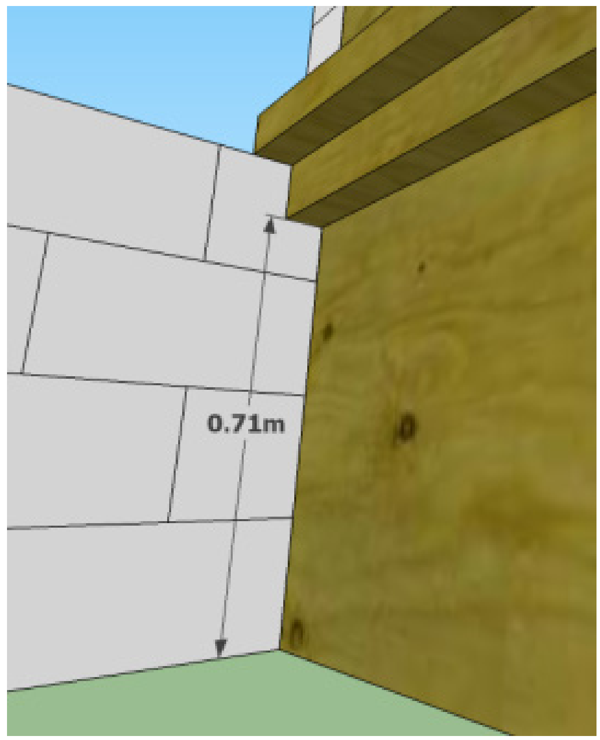

Figure 8 Location of first shelf

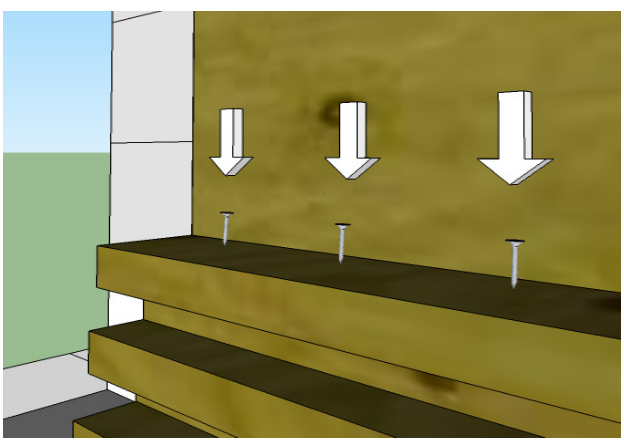

Figure 9 Shelf construction

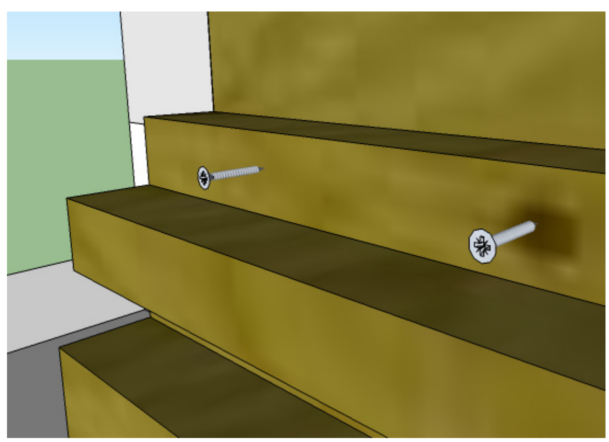

Figure 10 Self bracket construction

6. Cut the following:

    2 of 2x8x 1.2m

    2 of 2x8x 1.68m

    2 of 2x4x 2.5m

    1 of 2x4x 1.2m

    1 of 2x4x 1.28m

    2 of 2x4x 2.50m

7. Frame in the rear of the dryer. Lay a 2x8x1.2m across the tops of the bricks in the rear of the dryer. Using a 2x8 board for the header, and 2x6 boards for the sides. Bolt these directly to the blocks of the dryer. See Figure 10

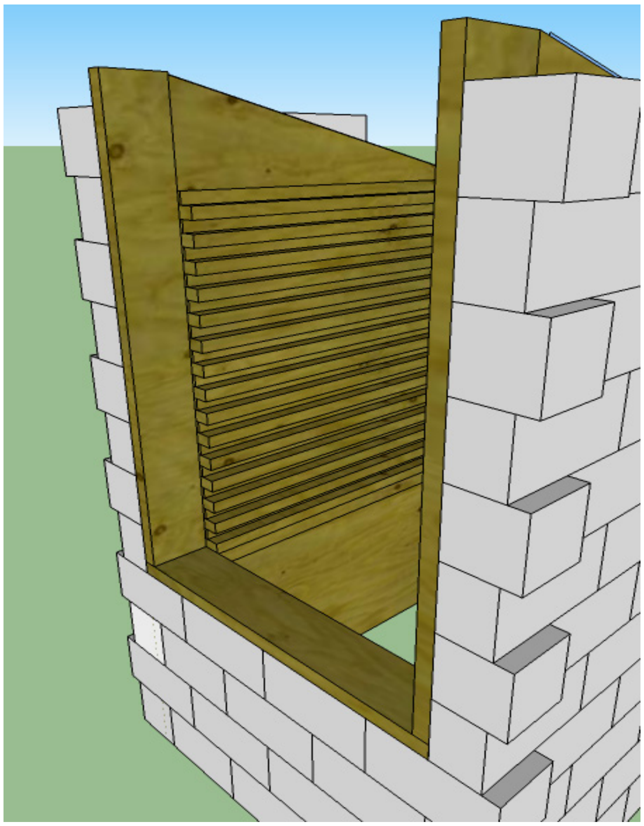

Figure 11 Rear dryer framing

8. Create the drying chamber door header by attaching the 2x8, 2x4s and 2x10 as shown in Figures 11 and 12. The 2x10 board will become the chimney support. Before attaching the chimney support, cut a 5cm by 5cm hole in its center as shown in Figure 13.

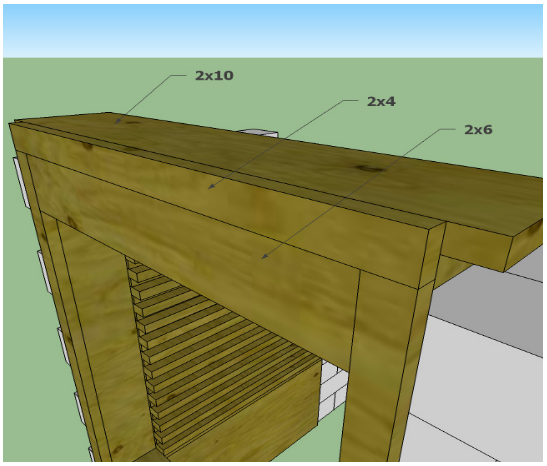

Figure 12 Dryer door header

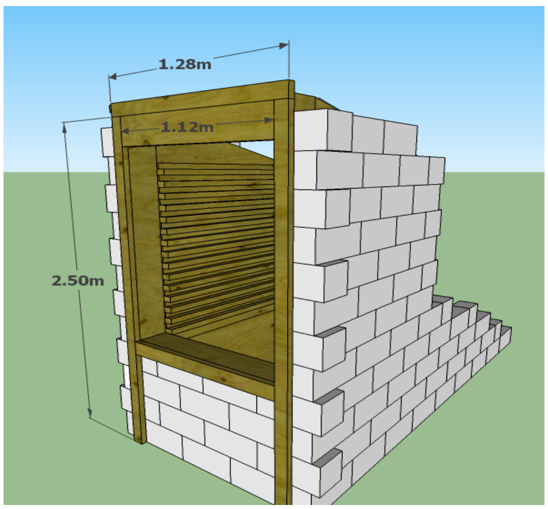

Figure 13 Dryer door frame

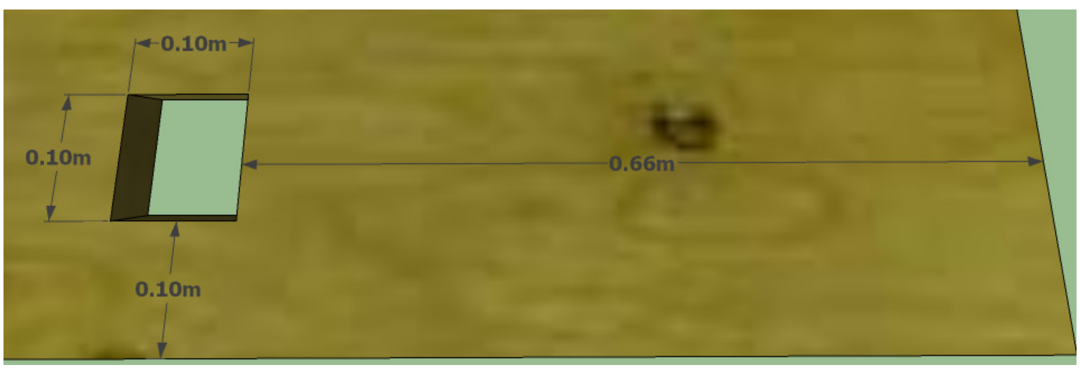

Figure 14 Chimney hole

9. Cut the 2 boards that support the polycarbonate refer to Figure 14 for exact dimensions.

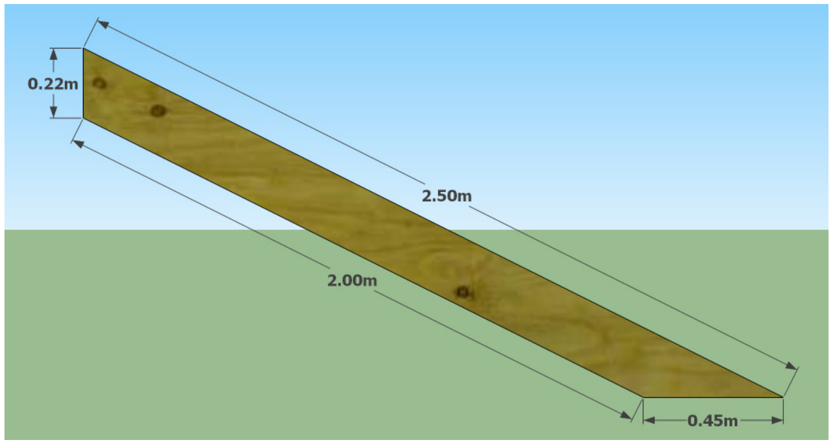

Figure 15 Collector covering supports

10. Install the polycarbonate support boards along the walls of the front of the dryer. The board will line up with the front of the dryer and attach onto the front of the drying chamber support shelves. See Figure 15

11. Install straw or foam insulation in a four inch layer starting from the rear wall of the dryer and working forward until reaching the front of the dryer. Cover this with sand. In the drying chamber the sand should be at least 10cm thick. To create the collector area, add sand from the straw up to the bottom of the collector boards. Refer to Figure 16 for additional guidance.

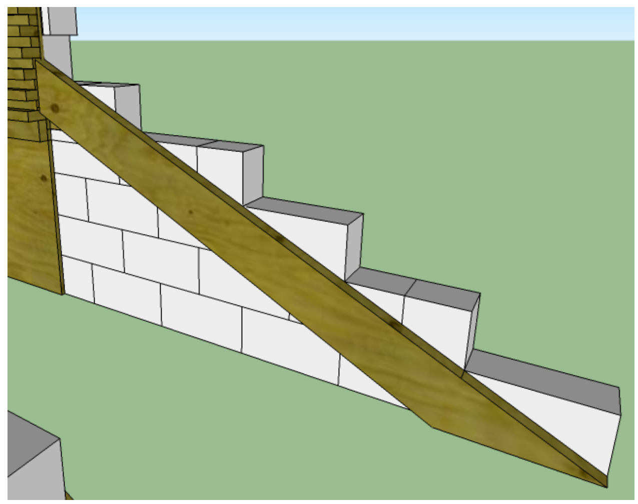

Figure 16 Collector support installed

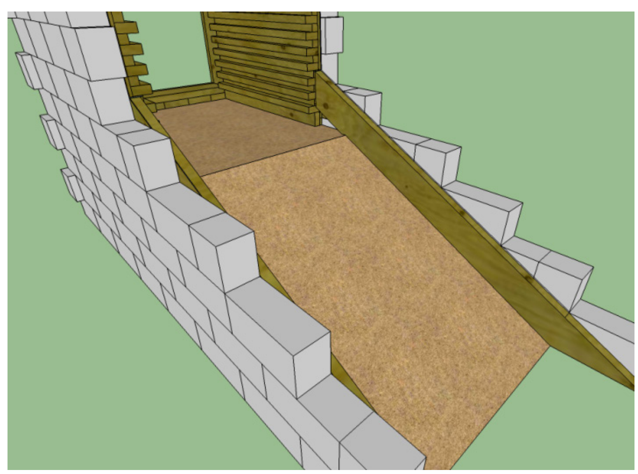

Figure 17 Sand installation

12. To make the collector corrugated metal can be placed directly on top of the sand, or it can be raised by placing 2 2x4s down as illustrated in Figure 17.

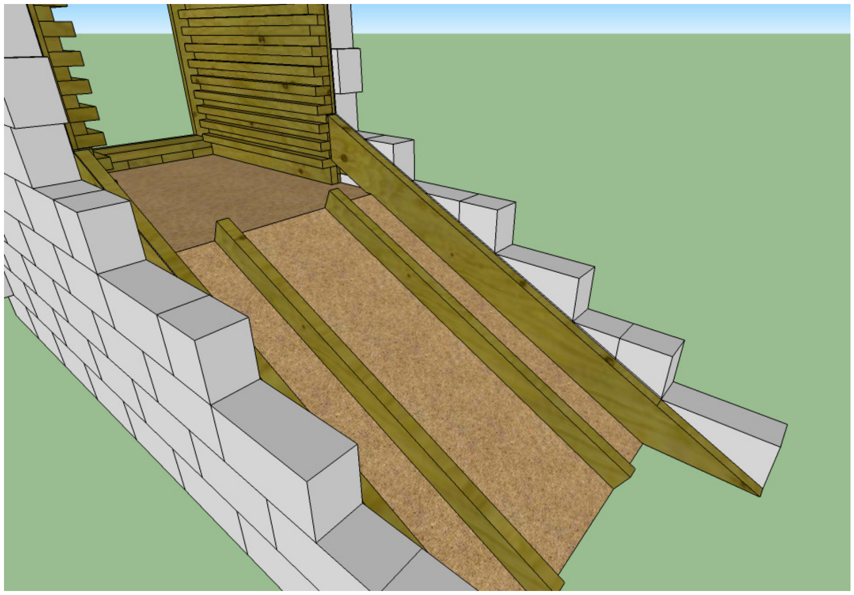

Figure 18 Collector supports

13. Paint the corrugated steel black then cut it to a length of 1.7m. Lay this piece on top of the sand (or raised on the 2x4 support). The smaller piece (the portion cut off previously) will lie on the sand at the bottom of the dehydration chamber. See Figure 18 for more details.

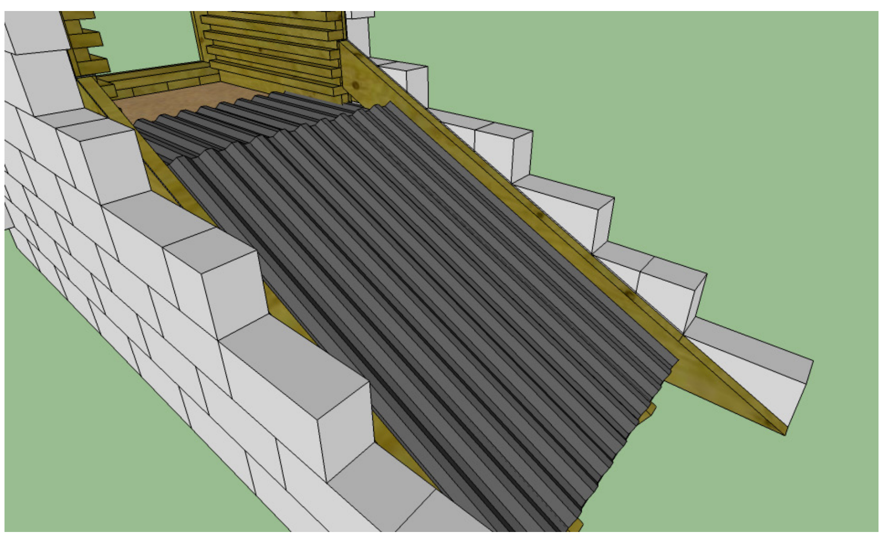

Figure 19 Collector placement

14. Next install the support for the glass in the top of the dehydration chamber. This is done by attaching a 2x2 that is 1.23m long to the top of the drying chamber support walls as shown in Figure 19. It is important to cut the ends of this support flush with the front of the dryer so that it can be used to support the drying chamber roof polycarbonate.

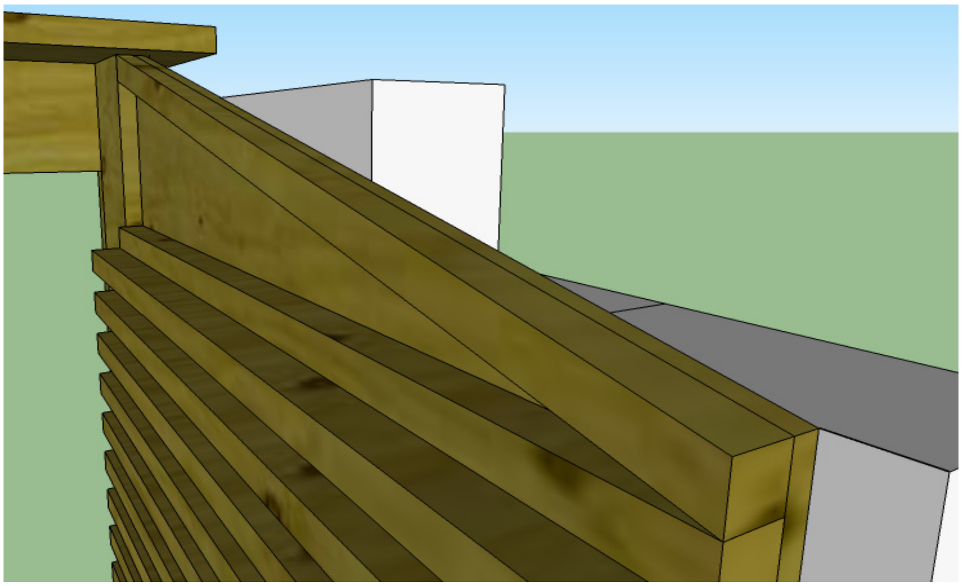

Figure 20 Roof polycarbonate support

15. Install a 2x2 support across the front of the drying chamber between the two walls, this is attached to the supports for the top piece of polycarbonate, this supports both the front and top polycarbonate once installed. See Figure 20

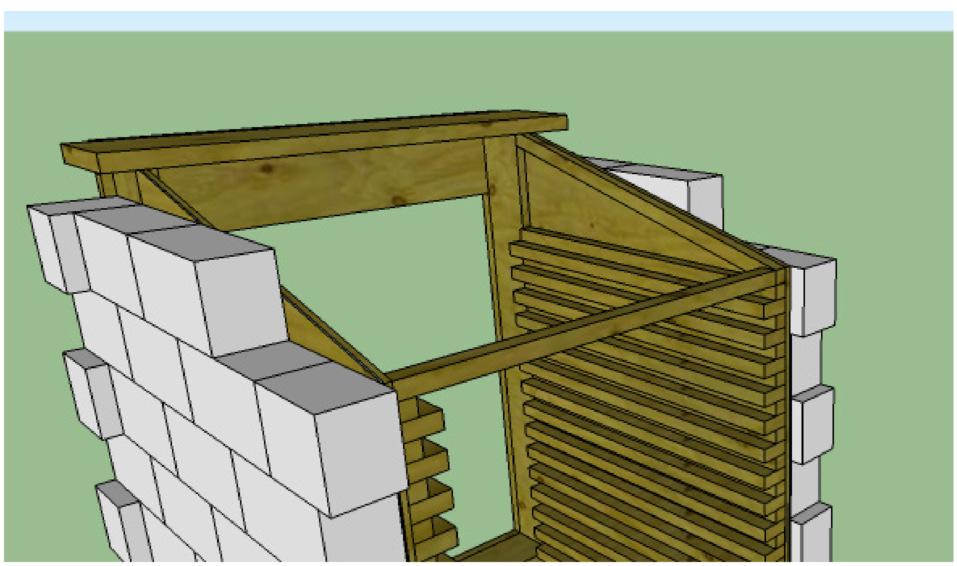

Figure 21 Front polycarbonate support (top)

16. Now install a second support at the top of the collector/bottom of the drying chamber to finish off the supports for the polycarbonate. See Figure 21.

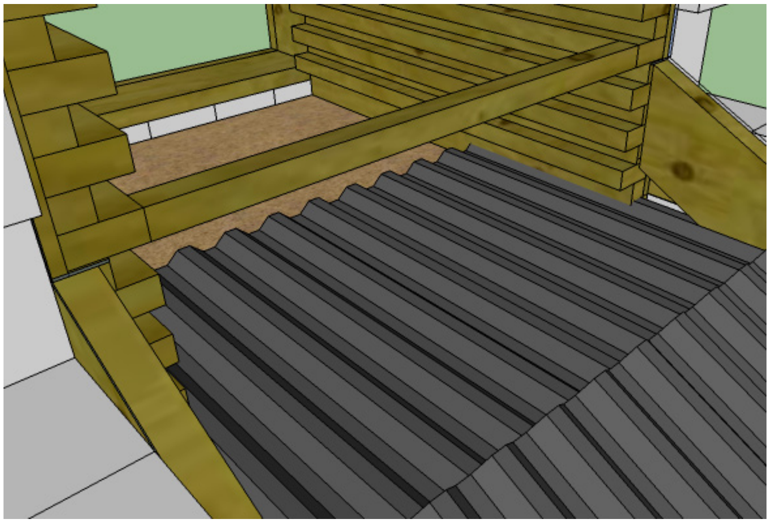

Figure 22 Front polycarbonate support (bottom)

17. Now paint all of the wood inside the dryer with a flat black paint.
18. Create the door of the dryer by cutting a 1.2m by 1.53m piece of plywood. Paint it black and then hang it from the 2x4 frame on the back of the dryer as shown in Figure 23. Install a latch to keep the door shut.

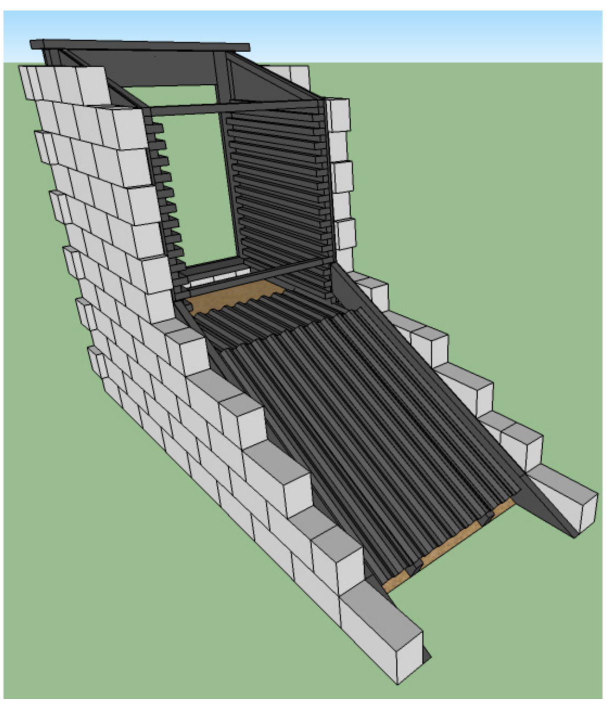

Figure 23 Dryer painting

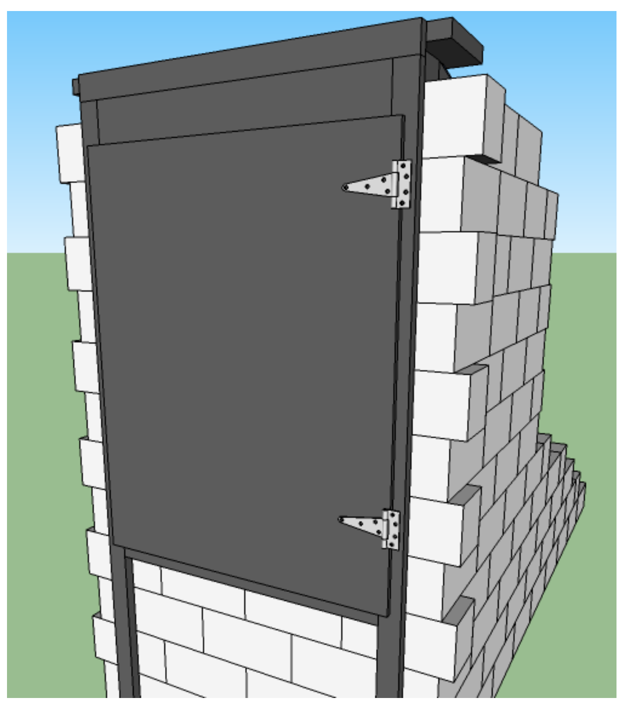

Figure 24 Dryer door

19. Construct the jig for supporting the chimney out of 4 sections of 2x2. Attach these to the top of the 2x10 chimney support around the hole that was cut earlier. There should be a 0.02m gap around the hole inside the 2x2 that was just installed. See Figure 24.

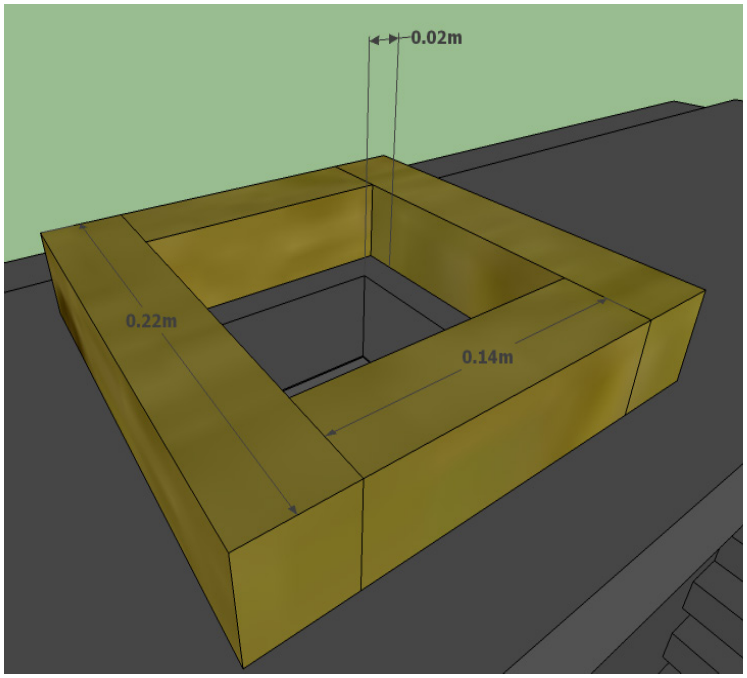

Figure 25 Chimney support jig

20. The chimney is made out 5 pieces of plywood. The two sides are 1.22m x 0.14m and the front and back of the chimney are 1.12m x 0.10m. Paint these pieces entirely black before assembling them. Screw these together so that the bottoms all align. See Figures 24 and 25. Attach a 0.14m by 0.19m cap (that has been painted black) to the top of the two side pieces. See Figure 26.

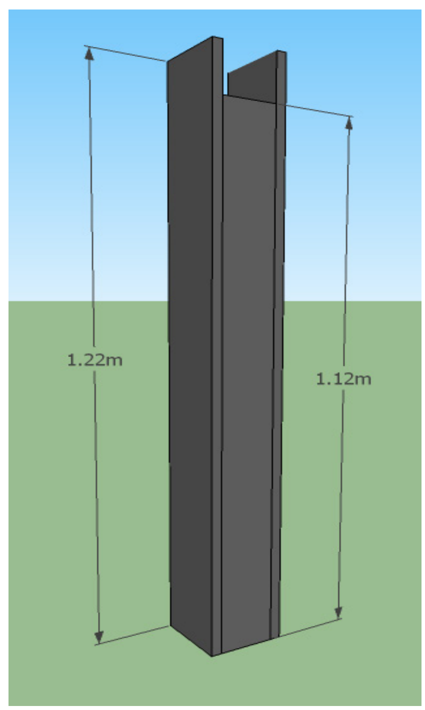

Figure 26 Chimney

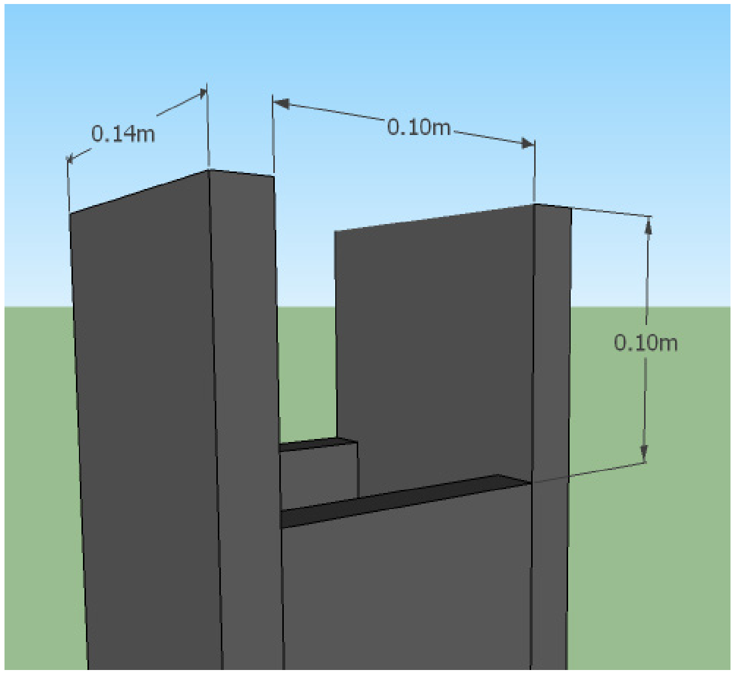

Figure 27 Chimney opening

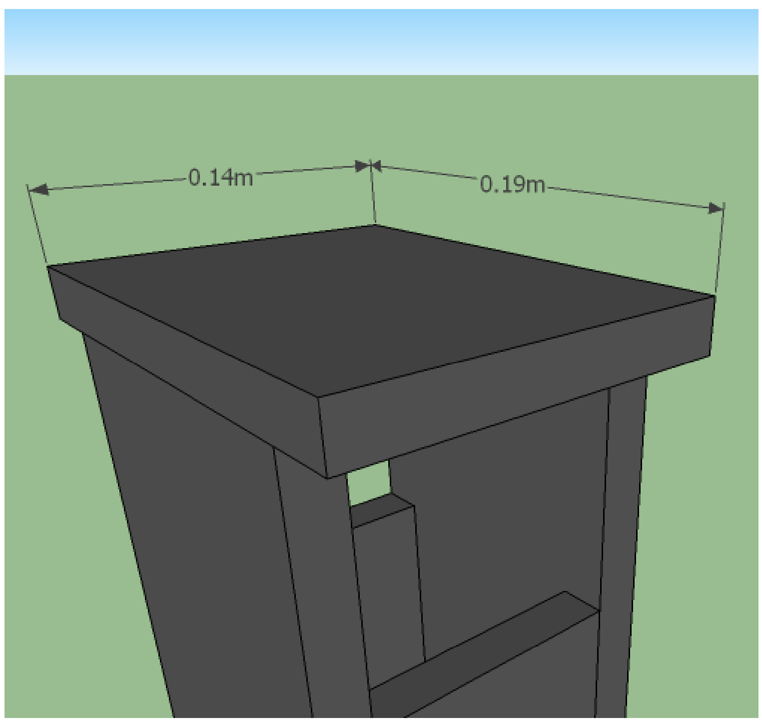

Figure 28 Chimney cap

21. Attach the chimney to the dryer by placing it over the hole cut into the chimney support 2x10 board at the top of the drying chamber. It should fit snuggly in the support jig placed around the hole earlier. See Figure 27.

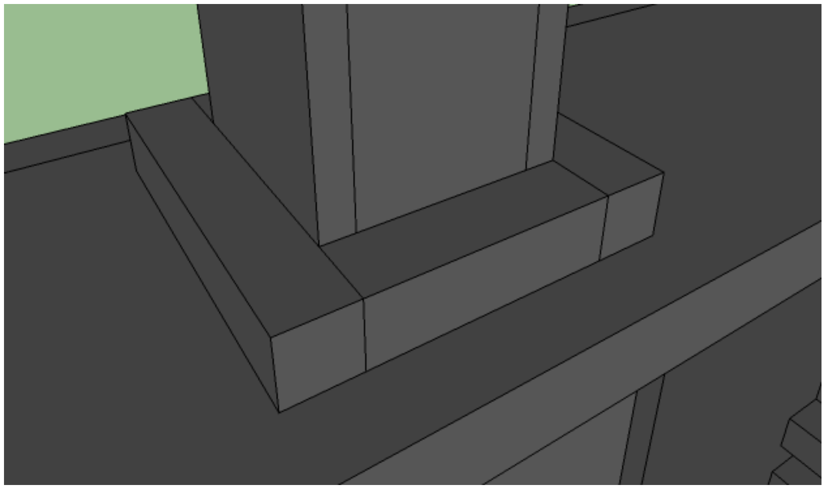

Figure 29 Chimney placement

22. Attach wire hooks to the top of the chimney (2 on each side) and to the outer edges of the chimney support board. Run wire between these hooks to further secure the chimney in place. See Figure 28.

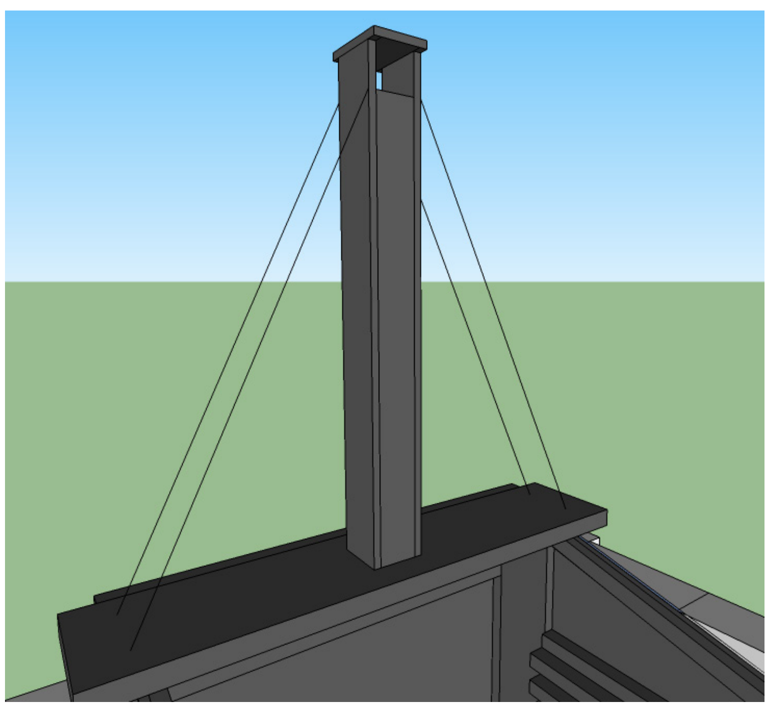

Figure 30 Chimney wire supports

23. The polycarbonate can now be secured in place. A 2.04m x 1.22m sheet of polycarbonate will be attached over the collector. The front side of the drying chamber gets a 1.11m x 1.22m sheet, attached directly to the ends of the shelves. The top of the drying chamber gets a 1.23m x1.22m sheet of polycarbonate, that will be attached to the supports, but should run up under the chimney support, enough so that it can be attached from inside the dryer. Attach all the polycarbonate by first caulking with silicone sealant along the where they will be attached and then screwing them into place. With polycarbonate it is important to predrill the holes so that it doesn't crack. After the polycarbonate is in place, seal any additional gaps with more silicone, so that the polycarbonate is as airtight as possible. See Figure 29.

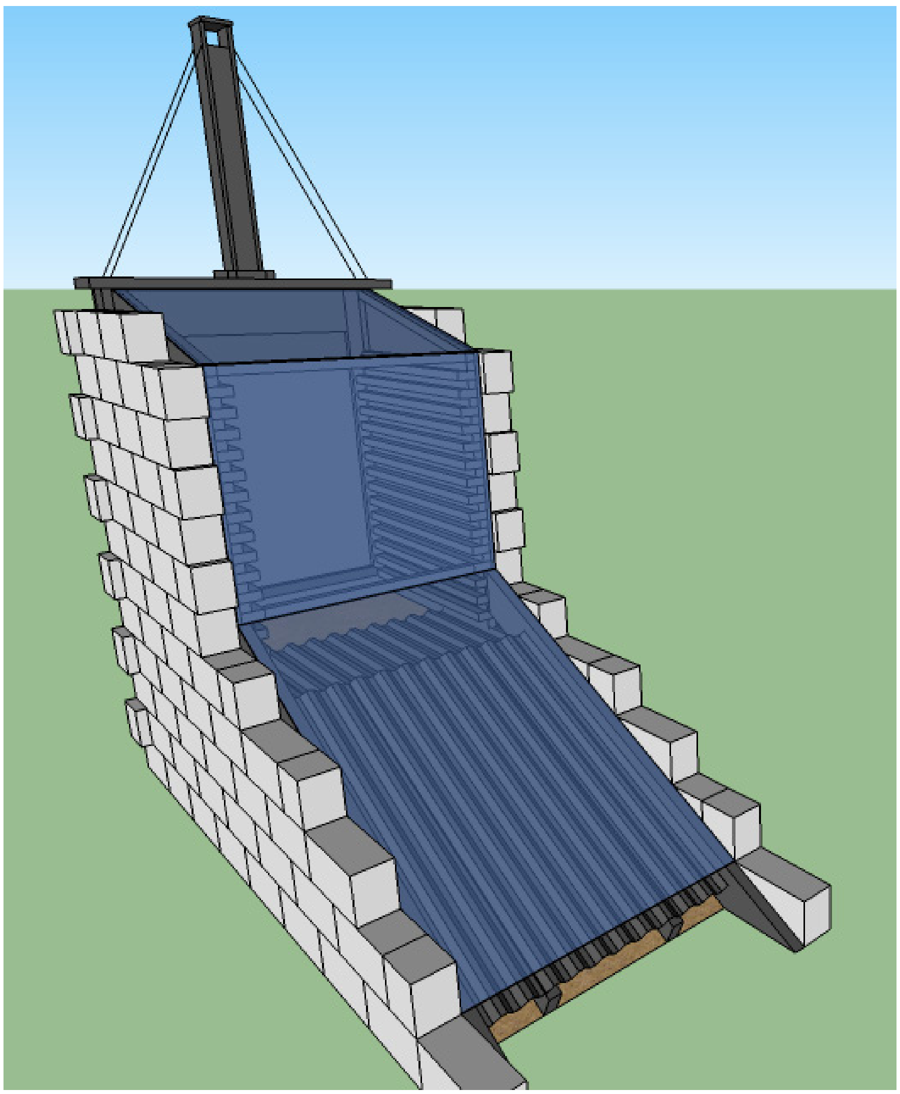

Figure 31 Polycarbonate placement

24. To build the trays, measure the width of the drying chamber shelves sot that the trays can be built appropriately for the dryer that has been built. Each tray takes 12 lengths of PVC to build. These are fitted together in the shape of a frame (Figure 30). Cut the PVC to the appropriate length and then dry fit into fittings and then check the fit in the dryer. Once the proper length has been established, cut and glue together all the trays. It would be a good idea to insert a dowel or small piece of rebar into the PVC along the sides of the tray to add strength. Cut Nylon netting to the correct size, it should just cover each of the trays. Attach the nylon mesh netting to the trays with zip ties and cut the excess off the zip ties. It is best not to store the trays in the dryer, as prolonged exposure can melt the PVC

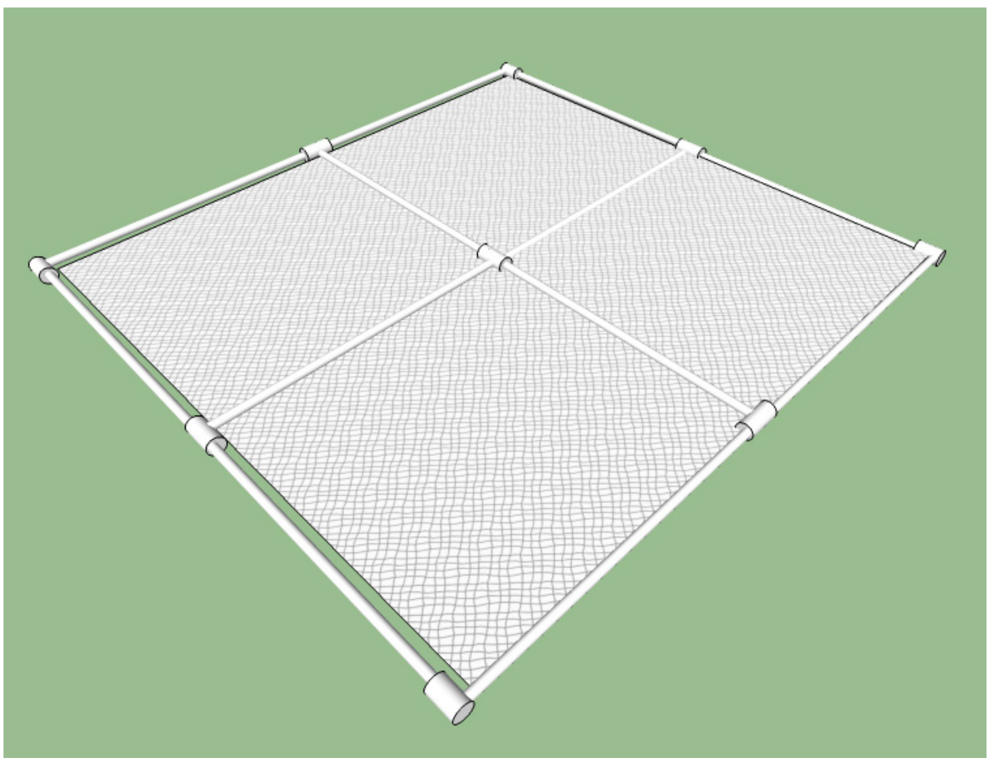

Figure 32 Tray

Solar Drying – Use Manual

Introduction

A solar dryer is an efficient way to prepare many foods for longer storage. This is a general manual to help with preparation of foods for drying, drying and storage of foods after they have been dried. The way the food is prepared, dried and stored will greatly affect the length of time it can be stored and later used.

Food Preparation

Peeling

If foods are eaten with the peel removed, then remove the peel prior to drying. This can be done in the same manner as when preparing the food for consumption without drying. For example tomatoes are used with the skin on in most all applications, so leave the peel on for drying. Another simple rule to follow for peeling is: If you take the peel off to cook it remove the peel to dry it. For example you would eat a raw apple with the peel on, but when you cook them you remove the skin, therefore remove the skin to dry an apple. If you are not sure whether or not to remove the skin, remove it.

Slicing

Foods need to be sliced thinly. This will allow the moisture to escape the food more readily. Foods between 3mm and 6mm will dry best. Another important note about slicing is to try and slice the foods as evenly as possible. If there is some food in the dryer that is sliced thickly and some sliced thinly, the thicker food will take longer.

Preventing Browning

In order to prevent browning of the food during drying, place sliced food into an acid (for example lemon juice or citric acid if available.)

Food Drying

Placement of Food onto Tray

After the food has been sliced and rinsed in an acid it can be arranged on the tray. It is important to arrange the food so that proper airflow can be maintained throughout the entire drying process. The tray should only be covered 60% by food. Do not let food overlap, those areas will not dry.

Drying the Food

Now that the food is arranged on the trays, slide the trays into the shelves of the dryer. If using less than 15 trays, arrange the trays evenly throughout the dryer. It has been shown that this dryer is more efficient the fuller it is. Most food takes between 1 and 2 days to dry, this of course depends on how it was prepared.

Weather Adjustments

Some adjustments to the length of time food is in the dryer will need to be made depending on the weather. If it is cloudy, the food will take longer to dry than on a full sunny day.

Removal of Food from the Dryer

It is important to remove foods from the dryer when they are dried to the proper level. A good rule of thumb for root crops (taro, cassava, potato, etc.) is the food should be dry and brittle when finished drying. It should snap cleanly, with little to no bending before breaking. For foods with higher sugar content (fruits and vegetables) remove the food when it is soft and leathery, with no visible moisture. When these foods are pressed together after drying they should not stick together. If they do stick together they need to be dried longer.

Food Packaging

Once foods have been dried, package them in order to maintain freshness longer.

Package

It is important to keep oxygen away from the dried food as much as possible. In areas where it is available Mylar™ (a foil-plastic laminate) is recommended. Mylar™ must be sealed with a heat sealer, which creates an airtight environment. If Mylar™ cannot be obtained, just about anything that creates an airtight seal can be used. For example: Glass jars, polyethylene plastic or Ziploc™ bags. If an airtight seal cannot be made, the shelf life of the dried foods will decrease significantly.

Oxygen Absorbers

It is strongly recommended that oxygen absorber packets be included in any sealed bag. These work by absorbing any oxygen present, reducing the chance that bacteria have to grow. Oxygen absorbers work best in conjunction with Mylar™ pouches, but will also work with other methods.

Environment

If Mylar™ has not been used; the most important thing in increasing the shelf life of the product is the storage environment. A dark, cool and dry environment is the most suitable for the preservation of dried foods. This means that storing foods in direct sunlight, wet or warm areas **will decrease the shelf life**. Another thing to consider is that rodents and other pests can chew through most plastics. Ensure the storage area is free of pests to remedy this problem.

Using Dried Foods

If the food needed to be cooked in order to eat it when it was raw, it will need to be prepared the same way after it is dried, with the addition of one step. Before cooking with dried foods they will need to be rehydrated. This is done in much the same manner as dried beans; cover with water and let sit out overnight. The food can then be cooked the same way as when it was raw. This is the case for most root crops (i.e., potato, cassava and taro).

Some vegetables and fruits can be used just like they were used in dishes like they are when raw, with the addition of a little water to help them break down. It will be noted that the flavor of the dried product of some foods like tomatoes is stronger than that of the raw food.

Fruits are commonly eaten in their dehydrated form.