

The Design, Construction, and Use of an

Indirect, Through-Pass, Solar Food Dryer

Dennis Scanlin

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Drying is our oldest method of food preservation. For several thousand years people have been preserving dates, figs, apricots, grapes, herbs, potatoes, corn, milk, meat, and fish by drying. Until canning was developed at the end of the 18th century, drying was virtually the only method of food preservation. It is still the most widely used method. Drying is an excellent way to preserve food and solar food dryers are an appropriate food preservation technology for a sustainable world.



Food scientists have found that by reducing the moisture content of food to between 10 and 20%, bacteria, yeast, mold and enzymes are all prevented from spoiling it. The flavor and most of the nutritional value is preserved and concentrated. Vegetables, fruits, meat, fish and herbs can all be dried and can be preserved for several years in many cases. They only have 1/3 to 1/6 the bulk of raw, canned or frozen foods and only weigh about 1/6 that of the fresh food product. They don't require any special storage equipment and are easy to transport.

The solar dryer which will be described in this article is easy to build with locally available tools and materials (for the most part) for about \$150 and operates simply by natural convection. It can dry a full load of fruit or vegetables (7–10 lbs) thinly sliced in two sunny to partly sunny days in our humid Appalachian climate or a smaller load in one good sunny day. Obviously the amount of sunshine and humidity will affect performance, with better performance on clear, sunny and less humid days. However, some drying does take

place on partly cloudy days and food can be dried in humid climates. The dryer was developed at Appalachian State University in the Department of Technology's Appropriate Technology Program. Over the last 12 years we have designed, built, and tested quite a few dryers and this one has been our best. It was originally developed for the Honduras Solar Education Project, which Appalachian State implemented several years ago. The prototype for that project was constructed by Chuck Smith, a graduate student in the Technology Department. Amy Martin, another Appalachian student, constructed the modified and improved version depicted in this article. Solar dryers are a good way to introduce students to solar thermal energy technology. They have the same basic components as do all low temperature solar thermal energy conversion systems. They can be easily constructed at the school for small sums of money and in a fairly short amount of time, and they work very well. While conceptually a simple technology, solar drying is more complex than one might imagine and much still needs to be learned about it. Perfecting this technology



Above: Yum...the apples are almost ready.

has been one of our goals and while we are not there yet, over the years we have come up with some designs that work pretty well. This article will describe guidelines for designing, constructing and using a solar food dryer.

Factors affecting food drying

There are three major factors affecting food drying: temperature, humidity and air flow. They are interactive. Increasing the vent area by opening vent covers will decrease the temperature and increase the air flow, without having a great effect on the relative humidity of the entering air. In general more air flow is desired in the early stages of drying to remove free water or water around the cells and on the surface. Reducing the vent area by partially closing the vent covers will increase the temperature and decrease the relative humidity of the entering air and the air flow. This would be the preferred set up during the later stages of drying when the bound water needs to be driven out of the cells and to the surface.

Temperature

There is quite a diversity of opinion on the ideal drying temperatures. Food begins cooking at 180°F so one would want to stay under this temperature. All opinions surveyed fall between 95° and 180°F, with 110°–140°F being most common. Recommended temperatures vary depending on the food being dried. Our experience thus far and the research of quite a few others leads to the conclusion that in general higher temperatures (up to 180°F) increase the speed of drying. One study found that it took

approximately 5 times as long to dry food at 104°F as it did at 176°F. Higher temperatures (135°–180°F) also destroy bacteria, enzymes (158°F), fungi, eggs and larvae. Food will be pasteurized if it is exposed to 135°F for 1 hour or 176°F for 10–15 min. Most bacteria will be destroyed at 165°F and all will be prevented from growing between 140°–165°. Between 60° and 140°F bacteria can grow and many will survive, although bacteria, yeasts and molds all require 13% or more moisture content for growth which they won't have in most dried foods.

Some recommended drying temperatures are:

Fruits and Vegetables: (except beans and rice): 100°–130°F (Wolf, 1981); 113°–140° (NTIS, 1982); temperatures over 65°C (149°F) can result in sugar caramelization of many fruit products

Meat: 140°–150° F (Wolf, 1981)

Fish: no higher than 131°F (NTIS, 1982); 140°–150° (Wolf, 1981)

Herbs: 95°–105°F (Wolf, 1981)

Livestock Feed: 75°C (167°F) maximum temperature. (NTIS, 1982)

Rice, Grains, Seeds, Brewery Grains: 45°C (113°F) maximum temperature. (NTIS, 1982)

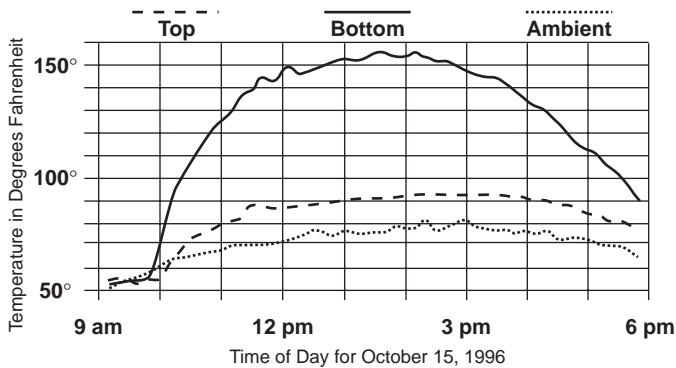
Temperatures Obtainable in our Appalachian Dryer

Our Appalachian dryer, with a reflector added, has reached temperatures over 200°F on a sunny 75°F day with all the vents closed. Preliminary experiences with a 4' long reflector have demonstrated a 20°F rise in the

Below: Adjusting the vents and testing (tasting?) the progress.



Chart 1



dryer temperature and a decrease in drying time. By fully opening the vents the temperature can be brought down to within 10° or 20° higher than the ambient temperature. The dryer can operate for most of the day between 120° and 155°F by opening the exhaust vents 1–2" (10–20 sq. in.). These are the temperatures at the bottom of the food drying area when the dryer has just been filled with food and a reflector is being used. The temperature drops significantly as it passes through the moist food. Chart 1 shows: the temperatures below the bottom tray of food, the temperatures above the top tray of food, and the ambient temperatures, right after a full load of 25 sliced apples (about 8 lbs) had been placed in the dryer. The dryer on this day had a reflector on it. It was a clear sunny day with relative humidities between 62 and 93%. By the end of the day, apples on bottom 5 trays were dry, some apples on top 5 trays were not. The temperatures were recorded with a Pace Scientific Pocket Logger, model XR220, 1401 McLaughlin Drive, P.O. Box 10069, Charlotte, NC 28212, (704) 5683691

Chart 2 shows a dryer operating in the afternoon of its second day of drying a load of food. One can see how the temperatures increase in the top of the dryer, as the food in the top of the dryer dries. This test was not using a reflector. By the end of this day all apples slices were bone dry, almost like crackers.

Possible temperature related problems

There are a couple of potential problems associated with higher temperatures. One study reported slightly higher vitamin C loss in fruits dried at 167°F than at 131°F. Greater vitamin loss has also been reported for the direct style of food dryer which exposes the food directly to the sun's radiation (ASES, 1983). However, there are many other factors that affect vitamin loss and the losses are different for different foods and different vitamins. I need to explore this topic more fully.

Case hardening is another potential problem associated with drying at higher temperatures. If the temperature of air is high and the relative humidity is low, there is the

possibility that surface moisture will be removed more rapidly than interior moisture can migrate to the surface. The surface can harden and retard the further loss of moisture. Solar dryers start off at low temperatures and high humidity and thus avoid this problem, I believe. At least I have not observed it.

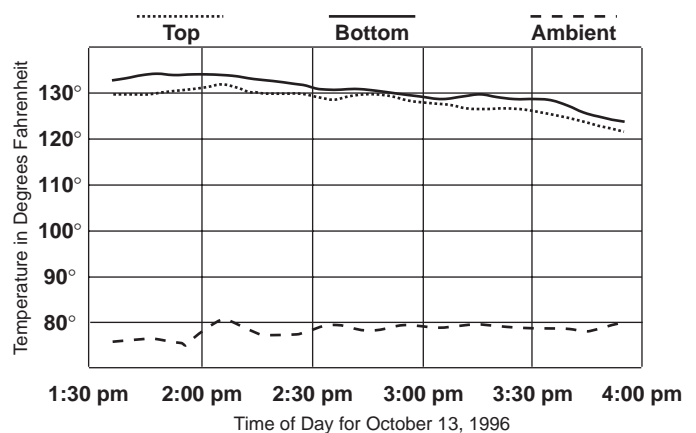
Air flow and velocity

The second of three factors affecting food drying is air flow, which is the product of the air velocity and vent area. The drying rate increases as the velocity and quantity of hot air flowing over the food increases. Natural convection air flow is proportional to vent area, dryer height (from air intake to air exhaust), and temperature. However air flow is also inversely proportional to the temperature in a solar dryer. As the air flow increases by opening an exhaust vent the dryer temperature will decrease. Ideally one would want both high temperatures and air flow. This can be difficult to achieve in a solar dryer.

Air velocity in a natural convection collector is affected by the distance between the air inlet and air exhaust, the temperature inside the dryer and the vent area. The greater the distance, temperature and vent area the greater the velocity. It is often measured in feet per minute (FPM) or meters per second. With constant temperatures, 230 FPM air velocity dries twice as rapidly as still air; at 460 FPM drying occurs three times more rapidly than in still air (Desrosier, 1963). Axtell & Bush (1991) suggest air velocities between 0.5 to 1.5 meters per second which is about 100 to 300 FPM. Desrosier (1963) suggests even higher air velocities between 300 to 1000 FPM.

The quantity of air, measured in cubic feet per minute (CFM) or cubic meters per minute, is the product of velocity and area of the exhaust vent. Morris (1981) recommends 2–4 CFM per square foot of collector for an efficient performing natural convection solar air heater. If the air flows are too slow the collector will heat

Chart 2



up and lose more heat to the air surrounding it. An efficient solar thermal collector should not feel hot to the touch. NTIS (1982) suggests 1/3 to 1/2 cubic meters per minute (11.5 to 17.5 CFM) per cubic meter of dryer volume as being a good flow rate for solar dryers.

Most designers of fossil fuel powered industrial food drying systems recommend considerably higher flows. Axtell & Bush (1991) of the Intermediate Technology Development Group (ITDG) recommend between 0.3 to 0.5 cubic meters per second or about 600 and 1000 CFM. Desrosier (1963) recommends 250 CFM per SF of drying surface. For the dryer described in this article with 18 SF of drying surface that would equal a little over 4,500 CFM.

Measured air velocities and flows in the Appalachian dryer

Our solar dryers are only able to achieve air velocities between 50 and 130 FPM with natural convection. Less than most of the 100 to 1000 FPM range recommended. Air velocities were measured in the solar collector's air flow channel with a Kurtz 490 series mini-anemometer.

Our dryer also has less total air flow than is recommended by most. During normal operation it allows 25–60 CFM. A tremendous difference from the 600 to 4500 CFM recommended for industrial drying systems. It has around 9 SF of glazing and should allow, according to Morris, 18 to 36 CFM for efficient collector performance. Our drying volume is about 3 cubic feet (0.08 cubic meters) and would according to NTIS need between 1 to 1.5 CFM. Quite a bit less than recommended by Morris for efficient collector performance and also less than our dryer's normal operating performance.

Increasing air flows and air velocity seems to have potential for increasing the performance of solar dryers. Unfortunately as the air flow increases the temperature

decreases in a solar dryer. Chart 3 depicts the temperature decline when the vents are fully opened from a 1 1/2" opening and then almost fully closed. We have found temperature to be more significant than air flow in affecting the speed or rate of drying and so we usually reduce the air flows by partially closing the exhaust vents to increase the temperature. By increasing the power or performance of our solar collector greater air flows will be possible while maintaining high temperatures.

Relative Humidity

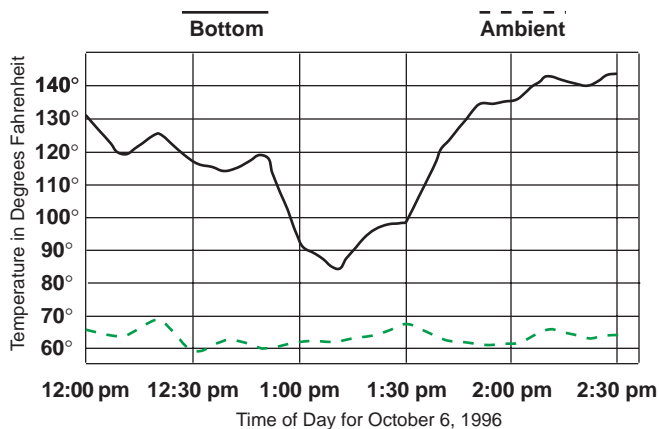
While not something one can do much about, the relative humidity is the third factor affecting food drying. The higher the humidity the longer the drying will take. More air will be required and the temperatures will need to be higher. Each 27°F increase in temperature doubles the moisture holding capacity of the air (Desrosier, 1963). In the Appalachian region where we have tested our dryers we normally have a relative humidity throughout the summer and early fall of 55 to 100%. This moist air can't hold as much moisture as less humid air could and as a result drying takes longer than it might in a dryer climate. This humidity also makes higher temperatures desirable for our climate.

How to get the correct temperature and air flow

The temperature obtainable in the dryer will be affected by several things: area of south facing glazing, insulation, air-tightness, area of vent opening, and ambient temperature. The area of south facing glazing is an important design decision. The dryer pictured has 9.2 SF of south facing glazing and approximately 3 CF of drying volume or 3 SF of glazing for every 1 CF of drying chamber. This is a good ratio. If one is interested in drying speed, increasing the ratio of glazing SF per cubic foot of dryer volume, adding more insulation and/or adding a reflector to the dryer would be desirable. This will allow one to increase the temperatures, air velocities and total air flow; and decrease the drying time. The temperature rise in the dryer described can be as high as 125°F above ambient with a reflector and all vents closed. Normal temperature rises without a reflector and with both exhaust vents opened 1–3" (12–36 square inches) would be 50 to 70°F. As mentioned previously, our preliminary testing indicates about a 20°F increase in temperature by adding a reflector. The maximum temperature observed was 204°F. The higher Delta T's and maximum temperatures will be reached with exhaust vent opening area reduced.

Designing for good air flows involves quite a few considerations. The air flow channel should be properly sized. The depth of the channel should be 1/15 to 1/20th the length of the collector. Making the air flow

Chart 3



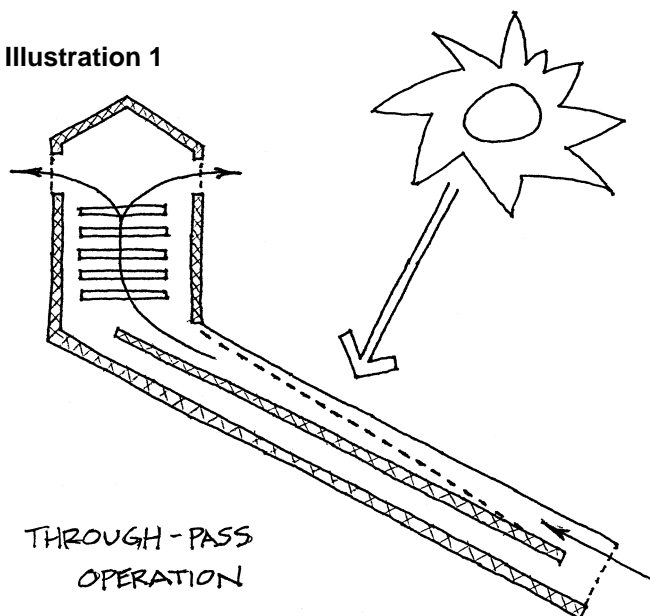
path as aerodynamic as possible is also desirable; especially for a natural convection collector. Although turbulence created by fins on the back of an absorber plate or corrugated metal has been shown to deliver as much as 40% more heat in active systems (Morris, 1981). One should try to keep the intake and exhaust vents spread as evenly as possible along the width of the collector to allow easy air movement. The intake and exhaust area and profile should ideally be the same or larger than the air flow channel. Air flow rates can be increased, while keeping temperatures up between 140°F and 175°F, by constructing a larger, more efficient, better insulated collector and/or adding a reflector to the collector. Increasing the size and/or performance of the collector can also increase air velocity by increasing the temperature inside the dryer. A larger, more efficient or powerful collector will allow one to more fully open up the vents thus increasing the CFM or volume of air moving through the dryer, while still keeping the temperatures high in the dryer. The dryer described here has 2 exhaust vents with a total of about 1.6 square feet of exhaust vent area. With the vents completely open the maximum temperature attainable on a sunny 70°F day is only about 85°F and so we normally decrease the vent area and CFM of air flow to increase the temperature and decrease the drying time. The area of exhaust vent during normal operation for several dryers we have designed and constructed is 10 square inches or less. This enables the dryer to achieve temperatures over 130°F and still allow air flow. It is desirable to have adjustable vent covers so one can adjust for different foods and weather conditions. Ideally the temperature in a food dryer should be controllable. The air velocity could also be improved by adding a fan, possibly PV powered as has been discussed in a previous HP article, or tall chimneys. Adding chimneys to a dryer and increasing the distance between the air inlet and exhaust will increase the velocity and volume of air moving through the dryer.

Collector design

The dryer uses a "Through Pass" collector configuration. Solar energy passes through a glazing material and is absorbed by 5 layers of black aluminum window screening diagonally positioned in the air flow channel. The air around the absorber, the black screen, is heated and rises into the drying chamber. A slight vacuum or negative pressure is created by the rising air which draws in additional air through the inlet vent and the aluminum mesh absorber. This air is heated and the process continues (Illustration 1).

Through pass mesh type absorbers can outperform plate type absorbers by quite a bit if properly designed because the air must pass through the mesh resulting

Illustration 1

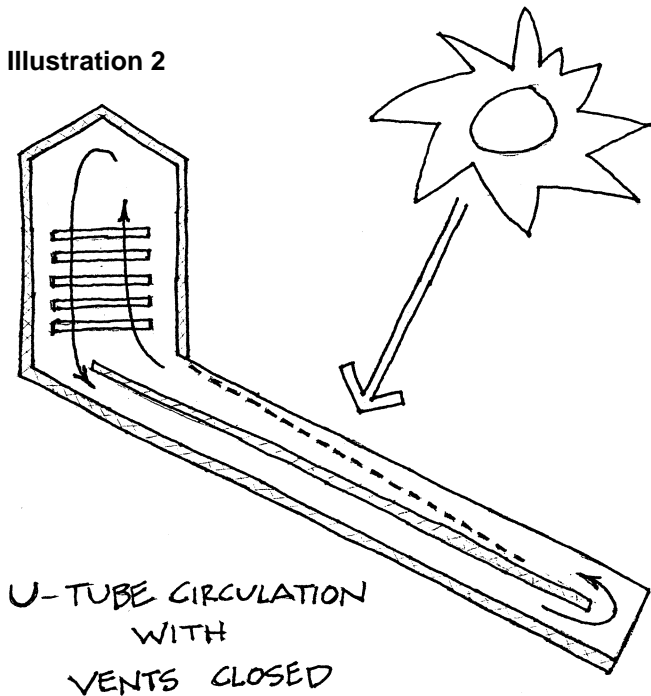


in excellent heat transfer (Morris, 1981). At Appalachian State we have compared the various absorber plate configurations and have found the diagonally positioned mesh type absorbers to produce the highest temperatures inside a box connected to the collector. Expanded wire lathe is recommended by some for the mesh but needs to be painted and didn't perform any better in our tests than the window screening. Using stock black or dark gray aluminum window screen eliminates having to paint the absorber and is less expensive and time consuming than other options. The bottom of the air flow channel can be painted black or some dark color to absorb any solar energy that gets through the mesh or possibly painted a light or reflective color to reflect sunlight back on to absorber mesh. Morris (1981) recommends a dark color, when we experimented with this we found similar performance with both strategies.

Another characteristic of our collector is its U-tube design. In addition to the air flow channel right below the glazing, there is a second air flow channel right below the first one and separated by a 1/2" thick piece of polyisocyanurate foam insulation board. This allows air to circulate when the vents are closed to increase the temperatures for pasteurization or to recycle air that has not absorbed much moisture in the latter stages of drying (Illustration 2).

When the vents are open most air will be drawn up in the top air channel and the bottom channel helps to reduce heat loss to the outside through the bottom of the dryer. The measured air flow velocity in this bottom channel was about 15 FPM with the two exhaust vents

Illustration 2



open 1.5" each and went up to about 25 FPM when all vents were closed. This seems to support the recycling theory. I'm not sure this feature is necessary; but, it doesn't seem to hurt the performance and may be helpful some times. We need to look at this some more.

One significant decision, in addition to size, which needs to be made when designing an air heating solar collector is what depth should the air flow channel be. The air flow channel depth for a through pass collector should be 1/20 the length of the collector (Morris, 1981). The collector pictured is 60" long and has a 3" air deep air space (1/20 x 60") in both air flow channels.

Any kind of glazing will work for this design. Appalachian's dryer has two layers of glazing; the outer is Sun-Lite HP, a fiberglass reinforced polyester (FRP), often referred to as Kalwall. It is available from Solar Components Corporation for about \$2.00/SF (121 Valley Street, Manchester, NH, 03103-6211, (603) 668-8186). The inner glazing is Teflon manufactured by the DuPont Company, (Barley Mill Plaza 30-2166, P.O. Box 80030, Wilmington, DE 19880-0030, (302) 892-7835). There is a 3/4" air space between the two layers and the glazings are caulked in place. The dryer should face due south for best stationary performance. The altitude angle of the glazing above horizontal should be the compliment of the average noon altitude angle of the sun at your latitude for the months you expect to be using the dryer or your latitude minus 10°, if you primarily intend to use it during the later part of the summer and early part of fall. For our latitude here in Boone, NC of 36° that would be 26°. The dryer pictured has an angle of 36°.

The sides and bottom of the collector and the sides,

door and top of the drying chamber are insulated with 1/2" Celotex Tuff-R polyisocyanurate foam insulation. It normally is covered with an aluminum foil. I am going to use 3/4" in the next one constructed. Making sure you tightly construct the collector by making good tight fitting joints, especially the door, and using caulks and/or gasket material is also desirable. And finally adding a reflector to the dryer and properly positioning it (about 20° above horizontal in early October to 40° in mid July at 36° N LAT) will improve the performance.

Materials Needed (approximate cost is \$150, excluding stainless steel shelf screen)

One 4' x 8' 3/4" CDX exterior plywood for sides, vent covers and door

One 4' x 8' 1/4" exterior plywood for bottom, roof and south wall of drying box

approx. 12 - 8' long 1x2 pine

Two 8' long PT 2x4 for dryer legs

Water resistant glue

Caulk or glazing tape

Eight 1/4" X 2 1/4" lag bolts and washers

24" wide by 30" long piece of black or dark gray aluminum window screen (.65/FT)

Ten 21" x 14.5" Stainless steel screen for drying shelves (\$6.62/SF) adds another \$150 to cost or could use a vinyl or vinyl clad fiberglass screen for about .35/SF

24" X 12 ft. 0.040 Sun Lite HP plastic glazing (\$1.85/SF)

Two 3 1/4" strap hinges approx.

Fifty 1 1/2" galvanized deck screws
paint

Two 2" hook and eyes

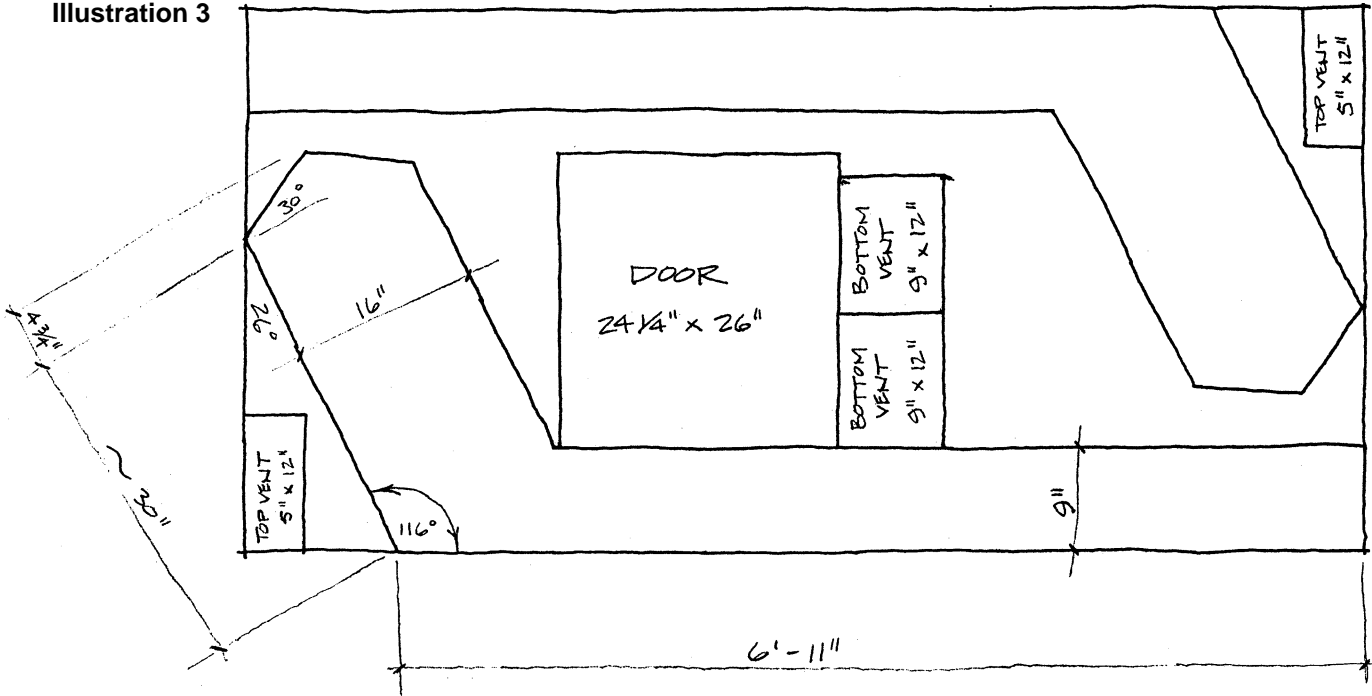
One 4' x 8' 3/4" celotex foil faced polyisocyanurate insulation board

Dryer Construction and Details

The dryer is primarily constructed of 3/4" exterior plywood, 1/4" exterior plywood, 3/4" celotex insulation board, dark aluminum screening, glazing, some 3/4" thick pine boards, and wood screws. The cutout illustrations (Illustration 3 & 4) dimension the layout of the important plywood and insulation pieces.

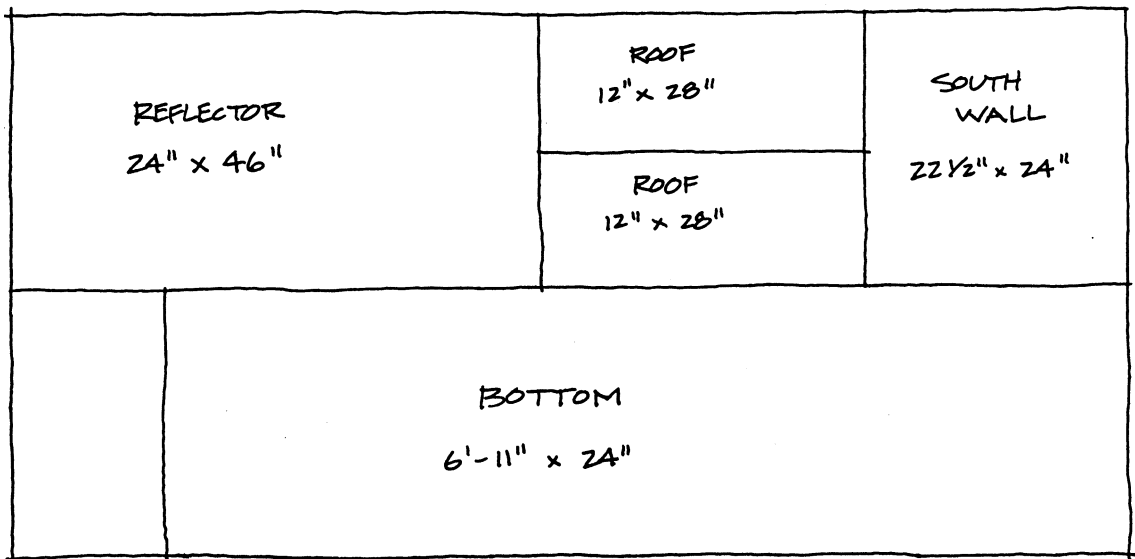
I tried to improve on the design depicted in this article by slightly increasing the glazed area (from about 9 to 10 SF), the SF/CF ratio (from 3 to 3.5 SF/CF), the thickness of insulation used (1/2" to 3/4") and lowering the collector altitude angle (from 36° to 26°) to improve late summer and early fall performance. I am also going to develop a larger and more permanent adjustable reflector. Verify the measurements before blindly cutting

Illustration 3



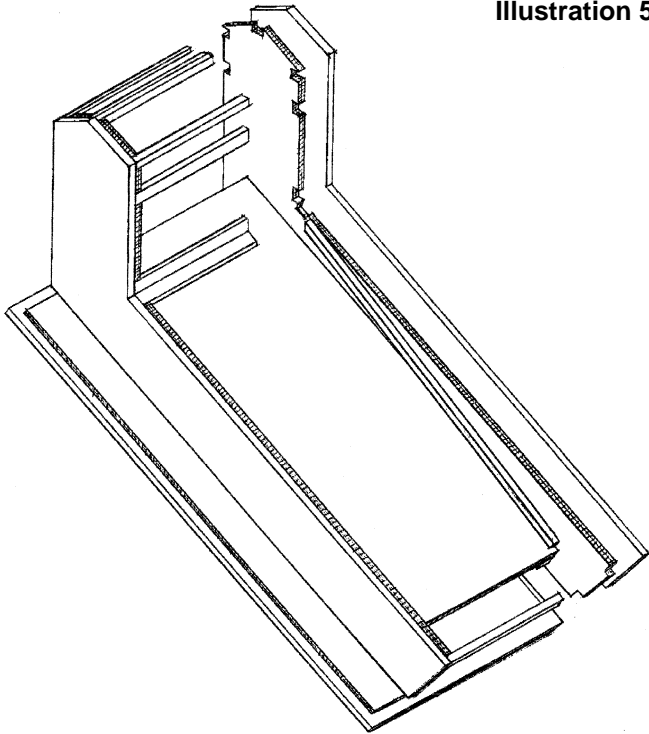
3/4" PLYWOOD LAYOUT

Illustration 4



1/4" PLYWOOD LAYOUT

Illustration 5



everything out. I tried to be as accurate as I could; however, there may be some mistakes. The exploded isometric drawing (Illustration 5) and the multiview (Illustration 6) illustrate the basic construction.

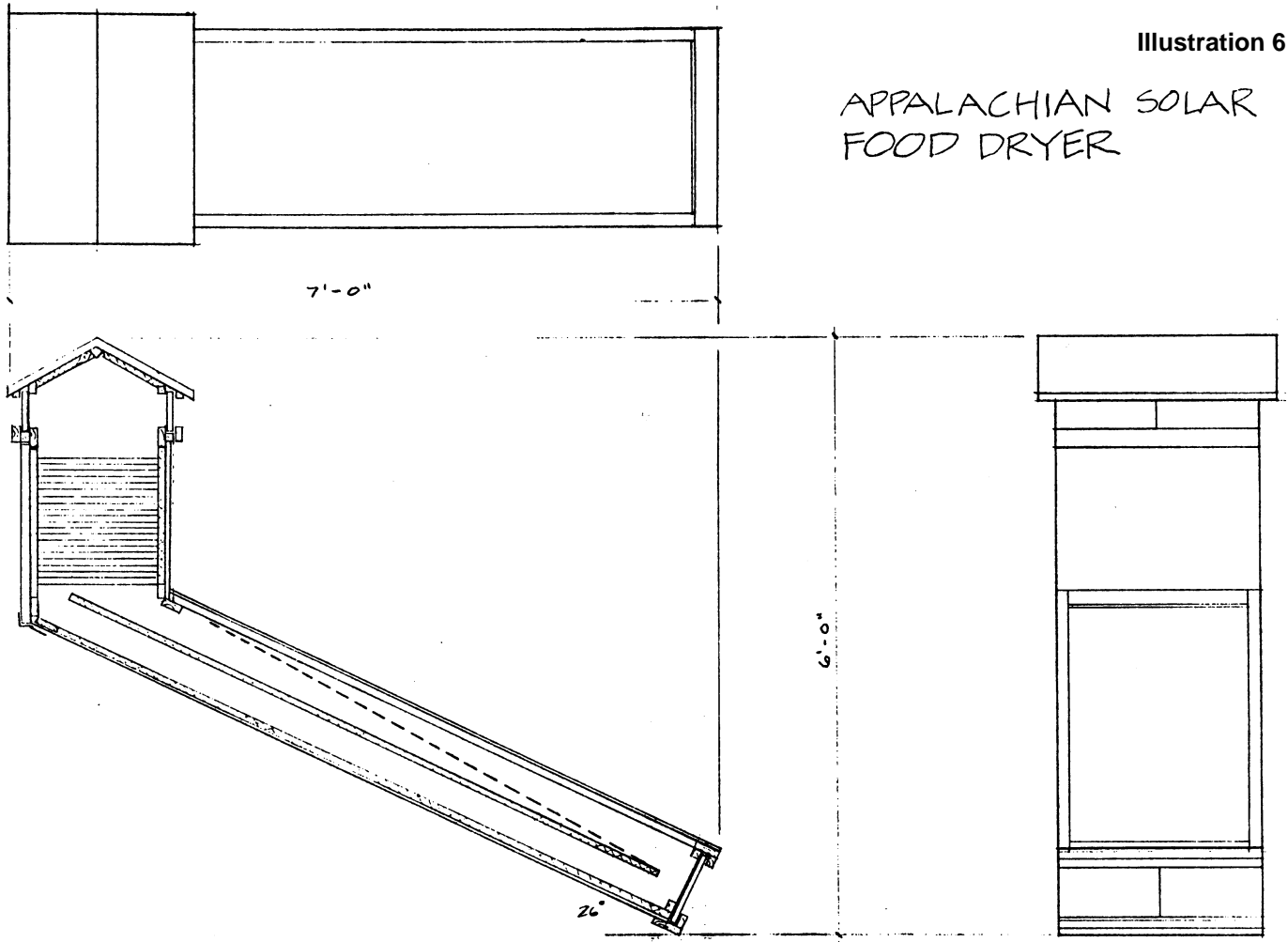
Basically begin by laying out the dryer sides, the door and the vent pieces on the 3/4" plywood. Cut these out with a skill or jig saw. Cut the 1/4" plywood bottom out with skill saw. Use the plywood side pieces to layout the insulation board dryer side pieces and cut with a razor knife. Glue the insulation to the plywood sides and then connect the sides together by gluing and screwing or nailing the plywood bottom on and screwing the 22 1/2" long wooden struts made from 1x2 stock in place. Illustration 7 describes the location of the most critical struts. Cut out insulation where the struts join the side pieces. Once the basic form is constructed everything else is applied as depicted in plans and photos.

Using the dryer

1) The initial phase of drying is more dependent on air flow than temperature, so keep the bottom vents completely open and the top about 1/2 open or more. After 1 to 2 hours reduce the top exhaust vent opening to 1"-3", leaving the bottom vents completely open, and

Illustration 6

APPALACHIAN SOLAR
FOOD DRYER



come out of a cut piece when squeezed. A few pieces squeezed together should fall apart and spring back when pressure is released. Vegetables should be brittle, or tough to brittle almost crisp like crackers or potato chips.

11) Put screen over the intake and exhaust vents to keep insects out.

Tips for Storing Dried Foods

- 1) Cool food to room temperature before packaging
- 2) Store dry fruits and vegetables in small, airtight, moisture, insect and rodent proof containers in dark, cool, dry and clean places. Glass jars, plastic bags, or plastic containers that can be sealed tightly are good. Store grains, roots, and legumes in places with good air circulation (NTIS, 1982).
- 2) Dried meats and fish should be stored below 5°C (41°F) to avoid rancidity (NTIS, 1982).
- 3) Most fruits and vegetables will keep for 6 months if stored at 70°F and 3-4 times that long at 52°F (Wolf, 1981).
- 4) Meat and Fish can be stored dried for several months in moisture proof, airtight containers. (Wolf, 1981)
- 5) If drying herbs store in uncapped jars for 24 hrs, if moisture collects, herbs need additional drying
- 6) Refrigeration or freezing will extend life of dried food.
- 7) Carefully label the food.

Influence of dehydration on nutritional value of food

While all methods of food preservation result in a degradation of the food quality and drying is no exception, drying food does increase the concentrations of proteins, fats and carbohydrates. Fresh peas are 7% protein and 17% carbohydrates; dried peas 25% protein and 65% carbohydrates. Fresh beef is 20% protein and dried is 55%. There is; however, a loss of vitamins. The extent of vitamin loss will be dependent upon the caution exercised during the preparation of the food for drying, the drying process selected, and storage of dried food. In general indirect drying methods such as the dryer described in this article retain more vitamins than sun drying or direct drying and also better than canning. Ascorbic acid, and carotene can be damaged by oxidative processes. Thiamin is heat sensitive and destroyed by sulfuring. The carotene content of vegetables is decreased by as much as 80% if dried without enzyme inactivation by blanching or sulfuring. Thiamin will be reduced by 15% in blanched vegetables and up to 75% in unblanched. In general more rapid drying will retain more ascorbic acid than slow drying. Usually dried meat has slightly fewer vitamins than

fresh. Fruits and vegetables are generally rich sources of carbohydrates and drying, especially direct sun drying, can deteriorate carbohydrates. The addition of sulfur dioxide is a means of controlling this deterioration.

Influence of drying on Micro-organisms

Living organisms require moisture; so by reducing the moisture we are able to reduce the ability of molds, bacteria, and yeasts from growing. Bacteria and yeasts generally require moisture contents over 30%. Drying food lower than 30% is no problem in a solar dryer. Molds however can grow with as little as 12%. Molds also require air, so as long as dried food is stored in an airtight container molds should not be a problem. Also if food was dried at over 140°F or if it was pasteurized prior to and after drying all 4 of the problem causing agents will be destroyed. Salt can be also used to control microbial activity if drying fish or meat. It is also important to start with clean food and utensils, and store food away from dust, rodents, insects and humidity.

Influence of drying on Enzyme activity

Enzymes are produced when plant tissues are damaged. Their production can lead to discoloration, loss of vitamins, and breakdown of tissues. Most enzymes are inactivated at 158°F. They also require moisture to be active and their activity decreases with decreasing moisture. But dried food still has some moisture so food deterioration due to enzymes can still be a problem. Browning of fruit for example and loss of carbohydrate content. One minute of moist heat at 212 F will inactivate enzymes. This can be achieved by blanching. Sulfuring also deactivates enzymes. Surprisingly dry heat does not affect enzymes very much. Short exposures to a dry 400°F has little effect. Blanching times vary. In general 1–3 minutes for leafy vegetables, 2–8 for peas, beans, and corn and 3–6 for potatoes, carrots, and similar vegetables.

Access

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Sun-Lite HP glazing is available from Solar Components Corporation, 121 Valley Street, Manchester, NH 03103-6211 • 603-668-8186

Teflon glazing is manufactured by the DuPont, PO Box 80030, Wilmington, DE 19880-0030 • 302-892-7835

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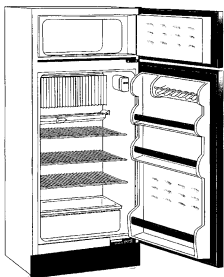
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