A Hybrid Solar Dryer for Processing Breadfruit

S. Michael McLaughlin
Co-founder, Trees That Feed Foundation

ABSTRACT

Fresh breadfruit is a healthful, widely accepted food in the Caribbean. During the main bearing seasons there is a glut of fruit, much of which is wasted, while outside of the bearing seasons there is little breadfruit in the local diet. Preserving the excess fruit will increase the food supply overall and make breadfruit products available year round. Fresh breadfruit contains 70 percent by weight of moisture. Dried breadfruit has a shelf life of one year or more, and has great food potential, for example by being ground into flour. Currently, equipment for peeling, chopping, shredding and grinding breadfruit is readily available. Drying the fruit tends to be the bottleneck to increased production capacity.

Given the cost and availability of electricity and fuel, solar drying has the greatest potential to increase the food supply of breadfruit, mango and other fruit. In this paper we discuss the importance, design, and usefulness of a cost effective hybrid solar dryer. Design criteria included low initial cost, simple construction based on locally available materials, rapid drying (within 24 hours), and the optional utilization of fuel. A modular design was developed based on detachable solar heat collectors, a cabinet with a lower section for collection, and upper section to hold food-safe stainless steel shelves, and a rooftop with a solar-powered exhaust fan and turbine vent to augment convection-based air movement. Construction materials include mainly plywood (preferably pressure treated or otherwise waterproofed), galvanized metal sheets, and clear plastic sheets (preferably UV stabilized). Construction skills needed are basic. The cabinet is 4 feet square, 10 feet maximum height, and the collectors' dimensions are 4 x 8 feet. The upper cabinet holds four shelves, each holding up to 25 pounds of fresh, shredded breadfruit. Total costs of construction fall below US$500.00, depending on local prices.

One, two or three solar collectors may be built, depending on available space and desired capacity. It is recommended that three similar collectors be built and installed on the west, south and east facing sides of the cabinet. This delivers maximum volume of solar heated air flow hence greatest drying capacity.

Solar energy is of course free, but not always available. An important design criterion was the optional use of fuel. The lower cabinet section is large enough to accommodate solar collectors on three sides, but also optionally a small kerosene or propane fueled heater. This increases operating costs, but avoids the potential spoilage of a crop of fruit that needs to be dried on a cloudy or rainy day.

Design calculations indicate a drying capacity of 100 pounds of fresh shredded breadfruit in 24 hours or less, the equivalent of 600 pounds of dried breadfruit per month. Field testing is underway, as of this writing.

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1. Breadfruit and the breadfruit tree

Fresh breadfruit is a healthful, widely accepted food in the Caribbean. Originally brought in the 1790's to feed the enslaved peoples, over time it has become a staple in the local diet in Jamaica, St. Vincent, and many other Caribbean countries. The breadfruit enjoys very wide acceptance also throughout the Pacific region, where it originated.

The breadfruit tree is virtually ideal as a source of locally grown, abundant and nutritious food in the Caribbean. Weather and other environmental conditions are conducive. The tree is hardy, resistant to disease and pests, requires little or no fertilizer, and once established is drought tolerant (although of course characteristics vary by cultivar). Low maintenance is evidenced by the common sight of large breadfruit trees growing by the roadside, getting no care whatsoever, but covered with hundreds of fruit in season.

The breadfruit tree suffers from few disadvantages. Two issues though have hindered a more bountiful supply of the fruit. First, the fruit is usually seedless. Traditionally, propagation is by adventitious shoots, which is slow and unpredictable. That issue has been mostly addressed through actively managed root culture and more recently by tissue culture in labs in the US, Germany and elsewhere.

The second issue is that breadfruit trees for the most part have a relatively brief bearing season. The bearing seasons typically occur in the Caribbean in June-July and December-January. There are exceptions, for example trees near rivers or otherwise well irrigated will produce fruit almost year round. Also the Ma'afala cultivar from Samoa seems to have a much longer bearing season, based on tests at Orange River Research Station, led by Mr. Zavier Gray. During the bearing seasons there is a glut of fruit, much of which is wasted, while outside the bearing seasons there is little or no breadfruit in the diet. As a result, imported foods especially carbohydrates like wheat and rice are used instead. Preserving the excess fruit will increase the food supply overall, and make breadfruit products available year round.

2. Nutrition and other characteristics of the fruit

Breadfruit has a bready texture and a mild flavor, tastes delicious with various seasonings, and is a nutrition staple. It is a carbohydrate with significant amounts of protein, vitamins and minerals, depending on the cultivar and local growing conditions. Currently breadfruit in Jamaica is picked fresh and almost always roasted, boiled or fried. Other countries have their own favorite preparation methods, for example in Puerto Rico the breadfruit is pounded into *tostitos,* while in Haiti *Tom Tom* is a favorite dish.

Fresh breadfruit typically contains 70 percent by weight of moisture. The fruit is delicious when freshly roasted, or cooked other ways, but ideally is consumed within just a few days of being picked. It's highly perishable and as a result difficult to export. A modest amount [775,000 kg in 2004, per STATIN Jamaica] is exported to the US, Canada, UK and elsewhere to the Caribbean diaspora, although the quality of the fruit at retail in those countries is typically very poor. It's also not very good when canned, and freezing as a way of preserving the cooked fruit can be expensive. The abundance of breadfruit during the bearing season contrasts with the scarcity, most months of the year.

Drying the fruit is an excellent solution for preservation. Dried breadfruit slices, chips or flour have a shelf life of one year or more, based on our personal experience. Breadfruit flour retains the nutrition of the fresh fruit, based on our analyses. The Breadfruit Institute, a unit of the National Tropical Botanic Gardens in Hawaii, has published extensively on the nutrition content of various cultivars. Trees That Feed Foundation has obtained standard food nutrition labels through the Jamaican Scientific Research Council that confirms the high nutrition content of breadfruit flour.

Given the cost and availability of electricity and fuel, solar drying has the greatest potential to increase the food supply of breadfruit, also mangoes and other fruit. In this paper we discuss the importance, design, and usefulness of a cost effective hybrid solar dryer.

3. Existing market value chain

Fundamentally, there needs to be a value chain for breadfruit and its products, otherwise the food will remain an artisan, local food, available in relatively small quantities. We see benefit in increasing the supply of breadfruit, although it may already seem plentiful, to reduce dependence on imported, increasingly expensive foods. Further, long-lived breadfruit products could become a large scale industry with local as well as export potential. To be successful, the industry must be independent of subsidies; there needs to be a production and distribution chain which is profitable at all stages, from tree propagation, planting, reaping, production and distribution of product.

Before breadfruit could become a commercially successful product the limits to the value chain have to be addressed. Supply of breadfruit in sufficient quantity from a traceable source is currently the weakest link in the production chain. That will change. TTFF is assisting in planting more trees (over 65,000 trees as of mid-2015) which will help the supply. Currently trees are planted in small quantities in random locations. We are encouraging co-ops and farmers to plant in orchard formation of at least one or more acres, to reduce the cost of reaping and transportation. TTFF is providing information on planting, care of the trees, pruning and reaping of the crop, working in conjunction with RADA, Jamaica's Rural Agricultural Development Agency, which will help with the availability of larger quantities of fruit.

For production of products from breadfruit, such as chips, or flour, drying capacity is the currently bottleneck. This hybrid solar dryer will help, at a medium scale.

Additional work is ongoing to develop the marketing and distribution of breadfruit products.

4. Preservation of fresh fruit

We make the assumption that there is, or will be a supply of fruit reaped safely, inexpensively and in good condition. The fruit needs to be transported promptly to a drying facility relatively nearby.

When picked the fresh breadfruit should be drained of its latex and kept cool (for example in cold water) until it is ready to be processed. Processing needs to occur within 2 or 3 days. Processing consists of peeling (which we have found is optional, for making flour), cutting into quarters or eighths, and feeding through a grater or food processor to produce slices or shreds. Our testing was carried out with 2 to 3 millimeter wide shreds, similar to those produced by a hand grater. Once dried, the shreds should be stored in airtight and moisture proof containers, away from light. Under good conditions the dried breadfruit shreds can be stored for extensive periods of time, a year or more. Later, the dried shreds can be ground into flour.

a. Sun drying

There is currently limited drying of fruit in Jamaica, and through the Caribbean as we understand it, although drying of many kinds of fruit is common in Asia and other parts of the world. Currently drying is typically sun drying, namely spreading out the fruit on a large, clean, flat surface exposed to the sun. A concrete rooftop is often used, although access may be difficult. It is a successful approach, because of the typically unobstructed sunlight. The concrete temperature rises in the hot tropical sun, warming the fruit from below as well as by direct insolation. The disadvantages are the unpredictability of rain showers, dust, overflying birds and insect contamination. Drying may be uneven unless the fruit is turned or raked periodically.

Depending on weather conditions, drying may not be complete within one day. Slower drying increases the risk of mold formation.

b. Solar drying

Solar drying refers to the use of solar heat, other than direct insolation. Solar drying typically relies on collectors of solar heat of some design that traps heat more efficiently and focuses it better, compared with direct insolation. TTFF has collaborated with the Engineering department of Northwestern University, Evanston, Illinois; reviewed designs from Professor Dr. Liu Xiangdong of China Agricultural University (courtesy of Mr. Zavier Gray, who participated in a course at the university); researched online; consulted with other designers; viewed other designs; and developed our own hybrid design, incorporating features of several preceding designs.

Recognizing that even in the warm tropical climates of Jamaica, Haiti and other Caribbean locations the sun is not always available, we looked for a design that was able to function when full direct sunlight was not available. This hybrid design provides the option of fueled heating, using a small propane or kerosene heater placed in the drying cabinet below the shelves of fruit.

c. Design criteria

Design criteria for this hybrid solar dryer included low initial cost, simple construction based on locally available materials, rapid drying (within 24 hours), and the optional utilization of fuel. A modular design was developed based on detachable solar heat collectors, a cabinet with a lower section for warm air collection and redirection, an upper section to hold food-safe stainless steel shelves, and a rooftop with a solar-powered exhaust fan and turbine vent to augment convection-based air movement. Construction materials include mainly plywood (preferably pressure treated or otherwise waterproofed), galvanized metal sheets, and clear plastic sheets (preferably UV stabilized). Construction skills needed are basic. The cabinet is 4 feet square, 10 feet maximum height, and the collectors' dimensions are 4 x 8 feet. The upper cabinet holds four shelves, each holding up to 25 pounds of fresh, shredded breadfruit. Total costs of construction are targeted to fall below US$500.00, depending on local prices.

5. Solar dryer features

The first challenge in building a solar dryer is choosing from among many possible designs. Professor Xiandong describes several classes of solar dryers, including active and passive dryers; tent, box or cabinet designs; and backup heating designs. This design is a composite of several different features.

a. Collection of solar energy

The benefit of solar drying is the more efficient capture of solar energy, with the potential of increased surface area of heat collection relative to sun drying. This dryer uses one, two or three collector modules, relying on a black box effect overlaid with a greenhouse type layer for capturing insolated heat.

b. Air movement over the fruit

Although it may seem obvious there needs to be sufficient air movement to transport moisture away. We've seen early dryer designs where the fruit was spread out and covered by a plastic sheet to trap solar heat, but with no provision for air circulation. The moisture did evaporate out of the fruit but then condensed on the underside of the plastic sheet and dripped right back onto the fruit. Air circulation has to be rapid enough to move moist air away, but not so rapid that the air passes over the collector so quickly that there is no warming.

Air flow in a tall dryer may occur through convection alone, however a fan preferably solar powered will augment the air flow.

c. Transportation of water vapor

Drying fruit means having low humidity air flow over the fruit. Warm air holds more moisture than colder air hence the use of the solar collector to raise air temperature.

We anticipate that in tropical areas the air can be warmed inside the dryer to a temperature of 110 degrees F, or more, which would decrease its relative humidity substantially. Depending on the incoming relative humidity, more or less air flow will be needed to completely dry the fruit. The fruit can be completely dried in conditions of partial ambient relative humidity—our rule of thumb has been, if the weather allows you to dry clothes on an outdoor line, it will allow complete drying of the breadfruit in a solar dryer.

In the Caribbean year round air temperatures near sea level fall within a narrow range, perhaps 70 to 95 degrees Fahrenheit. Humidity levels vary widely, from lows near 30 percent to highs near 100 percent.

d. Capacity

Given the large quantity of fruit during the abundant bearing season, a substantial drying capacity is needed. Drying capacity depends on a combination of factors, including ambient air temperature and humidity, temperature rise in the dryer, and volume of air flow.

Based on moisture transportation capacity of 1 pound of moisture per 1,000 cubic feet of air (see calculations in Appendix II), it is estimated that this hybrid dryer design can remove 1 pound of moisture in 3 minutes (under ideal conditions). Our target capacity for this dryer in the Caribbean is 100 pounds of shredded fruit per day; at 70 percent moisture content, 70 pounds of moisture should be removed in 210 minutes, or less than four hours.

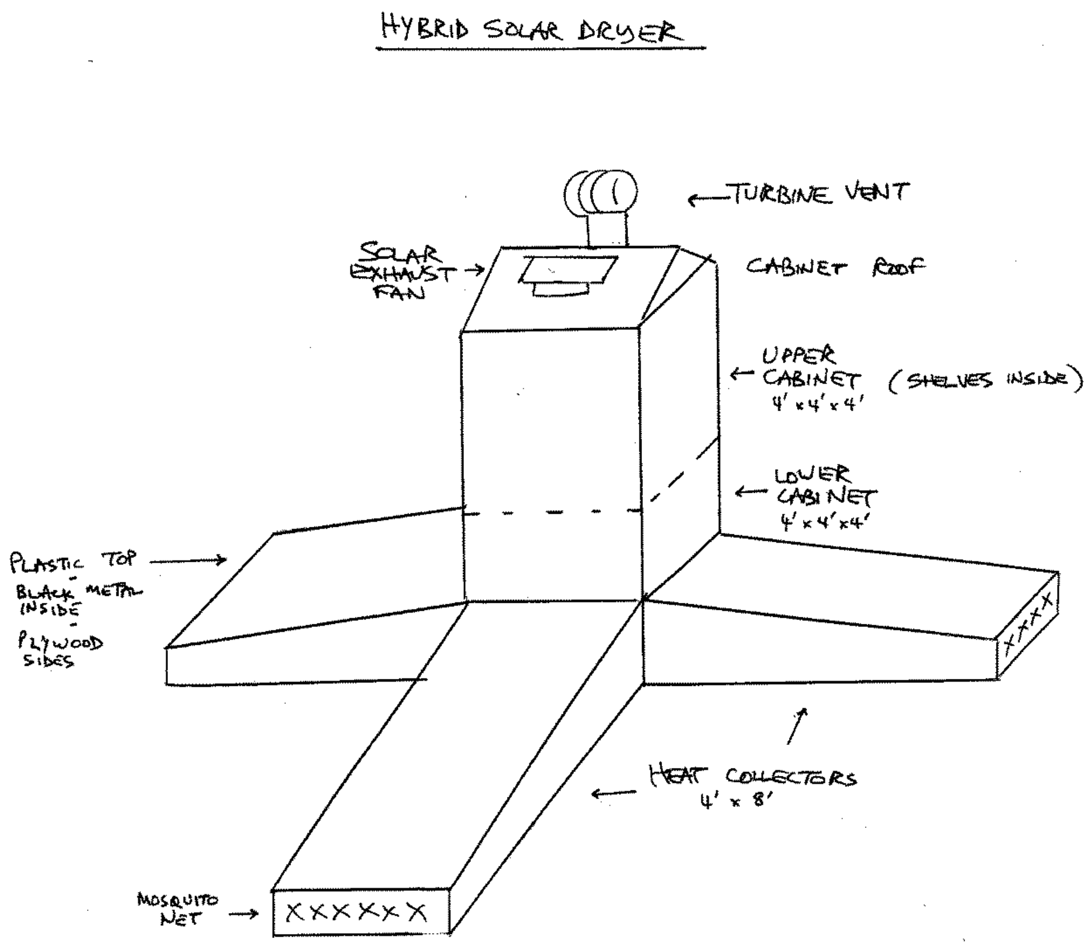
100 pounds of fresh fruit will yield approximately 30 pounds of dried fruit in a day, or approximately 600 pounds per month. A large farm would need more dryers of this type, or some alternative larger capacity drying equipment.

6. The hybrid dryer

Solar energy is of course free, but not always available. An important design criterion was the optional use of fuel. The lower cabinet section is large enough to accommodate solar collectors on three sides, but also optionally a small kerosene or propane fueled heater. The increases operating costs, but is preferable to the potential spoilage of a crop of fruit that needs to be dried on a cloudy or rainy day.

a. Features including supplemental energy source

The dryer is constructed in modules, for ease of construction and transportation, and also to allow ganging. The modules are collectors, lower cabinet, upper cabinet, shelves and rooftop. One dryer will use one, two or three collectors, depending on available space and intended capacity.



Each collector is composed of a corrugated metal sheet, painted black, housed in a plywood cabinet, covered by a sheet of clear plastic. Ambient air enters at one end and flows out the other. The collector top surface (clear plastic) slopes upward to enable convection air flow. See illustration nearby. The ideal angle for heat collection approximates the latitude of the location, to maximize the amount of direct sunlight (avoiding a cosine effect loss). As a practical matter in this design, the slope was approximately 8 degrees, primarily to keep the physical dimension of the dryer smaller.

It is recommended that three similar collectors be built and installed on the west, south and east facing sides of the cabinet. This delivers the maximum volume of solar heated air flow hence greatest drying capacity.

Warm air emerges from the wide end of the collector into the lower cabinet.

The lower cabinet is constructed of plywood with openings to allow collectors to be placed on three sides. In the Northern hemisphere the collectors fit to the south, east and west sides of the cabinet in order to receive maximum solar radiation. The rear of the lower cabinet (facing North) is closed using doors, but able to be opened easily if needed, to allow a propane or kerosene heater to be inserted. The optional use of fuel for heating is an integral part of the design. It allows drying on a humid, cloudy or even rainy day.

The upper cabinet is made of marine or treated plywood, for low cost. The front (south facing side) is made of clear plastic to allow for additional insolation. The cabinet holds four slots on which shelves slide. For the dryer to meet food safe specifications, it may be necessary to use stainless steel or other food safe material, although that would increase the cost.

Each of the four shelves are identical. There is a square wooden frame holding a stainless steel (or food safe plastic) mesh cover. The shredded fruit is spread out evenly over the mesh. According to work by Prof. Xiangdong, the ideal loading is 10 kg per square meter. Given the dimension of this drier, and converting metric to English units, (4 feet square external dimension) the full load for each shelf is estimated at 25 pounds. Of course testing this assumption under local conditions will be necessary.

The rooftop is of simple construction, namely plywood and sheet metal. The roof holds two units for air extraction, a solar powered fan and a wind powered turbine vent. Combined, the estimated air flow is 500 CFM (cubic feet per minute) in full sunlight with a light wind.

The size was determined by the criterion that readily available materials should be used. Plywood is typically sold in 4 by 8 foot sheets, which helped dictate dimensions. Corrugated metal and corrugated plastic roofing material is similarly sold in 8 ft lengths. The core of each collector is a corrugated metal sheet sized 4 by 8 feet. The frame holding the metal and plastic sheets is constructed of marine plywood, 8 feet long, one foot high at the lower (intake) end, tapering up to 24 inches high at the higher (outlet) end.

The cabinet is 4 feet square (outer dimensions). Each of the lower and upper cabinets are designed to be 4 feet tall, although the prototype units were only 42 inches tall, for ease of construction and assembly. The upper cabinet stacks atop the lower cabinet and of course the roof module sits atop the upper cabinet. The total height approximates 10 feet. With this design, purely convectional air circulation probably would not suffice, hence the use of exhaust fans.

Detailed engineering drawings including exact dimensions will be available at a later date.

Photos below show a front view and side view. All modules are visible, roof, upper and lower cabinet and solar collector. The shelf loaded with sweet potato is partially visible through the front window. At the time the photos were taken, the shadow of a tree partially covered the collector.

b. Materials and costs

The initial objective for total materials costs for this dryer was US $500. The actual costs of building the prototype turned out much higher, as summarized in Appendix I. The materials costs totaled $1,066. Labor costs are a rough estimate. The number of hours spent in construction is an actual count, but an experienced carpenter or cabinet maker would likely be more efficient. The hourly rate is an estimate as no firm commitment has been negotiated.

Materials prices were determined in the US and not locally. Although some local prices will no doubt be higher, we believe that a small scale builder of a dryer may be able to salvage and reuse some materials, for example the corrugated metal (“Zinc”) sheets. Also it seems very likely that other material substitution will be possible. So for example UV stabilized polyethylene plastic sheets come in flexible rolls, and would be much cheaper (although less durable) than corrugated polycarbonate sheets. Food safe plastic mesh is much less expensive than stainless steel mesh. It seems to us that materials costs could be reduced by several hundred dollars, bringing the cost closer to the initial goal of $500.

Production costs, if multiple dryer kits are being constructed, would decline also.

c. Cost effectiveness

Although market studies have not been completed as of this writing, our practical experience is that there will be plenty of demand for breadfruit flour for various applications. Already Ms. Ivy Gordon, of Jeffrey Town in the parish of St. Mary, Jamaica, has developed a recipe for breadfruit porridge whose main ingredient is breadfruit flour produced locally. We have tasted the porridge ourselves. It has a mild flavor, which can be enhanced by vanilla extract, cinnamon, nutmeg or other spices. It tastes similar to cornmeal porridge, perhaps somewhat thinner, and lighter in color. TTFF is currently distributed this porridge mix to a number of basic shools in Jamaica, and we have been told that the breadfruit porridge is well accepted by the young students.

We've also distributed samples of breadfruit flour to high end restaurants and hotels. Universally the chefs have expressed keen interest, with the reservation that an adequate supply of consistently pure, high quality flour has to be available before the product could be added to their menus.

TTFF estimates that a market price of US$2.00 per pound is acceptable, although we have paid somewhat more as an incentive to stimulate this nascent product market. A 3 or 4 pound breadfruit costing $0.50 to $0.75 will yield one pound of flour, so the differential over the price of the fruit should allow for processing and transportation costs, plus a profit margin. This assumption will need to be further tested in practice. Wheat flour is produced efficiently in vast quantities in the developed world, and oftentimes is subsidized by Governments, making it a very low cost alternative. However it does require hard currency to purchase. Locally produced flour can substitute for at least a portion of those imports.

No doubt other higher value added products can be produced from breadfruit flour, for example pastries, pasta, flatbreads, crackers, pancake mix and more.

Very rough calculations say that a producer could profit by $0.50 per pound; if the production is 600 pounds per month, profit of $300 per month would indicate payback for the initial cost of the dryer within 3 to 6 months of starting production.

7. Test results

Initial tests were conducted to measure the performance of a single solar collector. As indicated below, ambient air temperature was raised by up to 25 degrees F. Relative humidity decreased from 42 percent to 16 percent, which should give plenty of drying capacity.

In the warmer climates of the Caribbean, sunlight is much more intense than in Chicago's Spring weather, so the ambient temperature will be higher, and the temperature increase may be higher. On the other hand, during this test the observed air flow was very slow (below the 2 mph reading threshold of the anemometer) based on convection alone. In practice air flow will be aided by exhaust fans; with a more rapid flow the temperature increase may be lower.

a. Dryer performance testing

Springtime weather in Chicago in 2015 was relatively cool and wet. There were very few days where temperatures reached 80 degrees F, which we considered the minimum for a reasonable test. Nevertheless we did conduct testing. The results below were taken on July 2, 3 and 4, 2015, all days with hazy sun and no rain. On the first day, ambient air relative humidity varied between 74 and 57 percent, while temperatures during the test ranged mainly between 64 and 66 degrees F throughout, hardly ideal. On the second and third day relative humidity ranged 74 to 54 percent. Temperatures ranged 70 to 80 degrees F.

Breadfruit was unavailable so we used sweet potato as a substitute. The sweet potato available in Chicago is a different variety than common in Jamaica; it contains more moisture and we felt would be a good test of a dryer. We shredded a total of approximately 11 pounds of fruit for this test, in two batches. The intent was to weigh before and after, to test drying effect. It is estimated that the moisture content is similar to breadfruit, at approximately 70 percent by weight when fresh.

We used a kitchen food processor with a medium shredding blade. The size of the shreds is estimated at 2 mm wide and 1 to 2 cm in length. This size should give a high ratio of surface area to weight, while large enough that the shreds won't fall through the screen. We shredded 11 pounds in approximately 15 minutes.

The shreds were spread fairly uniformly on the stainless steel shelf. When wet some of the shreds would clump so a kitchen spatula was used to attempt to spread uniformly. We noted a few shreds falling through so we moved the shreds on top of a plastic mosquito netting. Despite the double layer, tiny fragments of sweet potato would fall through when the shreds were agitated.

It was also observed that 9 pounds of shreds are much more bulky than 9 pounds of fresh fruit. The shelf, at approximately 44 inches square, was moderately loaded at that point. We will need to revise our earlier estimate of loading 25 pounds of fruit on each shelf. Further testing is needed.

We agitated the shreds approximately every 2 hours, to aid even drying. Despite the agitation we noted that shreds near the edges dried better than those nearer the center. Most likely the spreading was not fully uniform.

The hybrid dryer was set up on a driveway almost fully exposed to sunlight. For approximately 30 minutes around 11:00 am local time there was partial shade from a tall tree, otherwise it was full sunlight. At approximately 1:00 pm local daylight saving time, the altitude of the sun reached its daily maximum of approximately 68 degrees.

For this test only one solar collector was used, and one shelf loaded with fruit. Ultimate we hope to use three collectors and four shelves of fruit for full capacity. During the test we touched the surface of the black painted metal and it was uncomfortably hot to the touch. In hotter tropical climates the metal surface would be 10 to 20 degrees F hotter, probably enough to cause skin burns.

Doors at the rear of the cabinet had not yet been mounted so the rear was sealed with heavy (6 mil) plastic sheeting. The cabinet was sealed against ambient air entering except through the solar collector, but as a practical matter the sealing was not perfect. An improved prototype will have tightly sealed joints.

The solar exhaust fan was checked periodically and it always operated at a high speed, although we believe not its full capacity of 350 CFM. We would also observe that the turbine vent typically spun very slowly. For most of the test period ambient wind speed was very low, estimated at 0 to 2 knots, with occasional gusts estimated at 5 to 7 knots. It was not possible to measure the flow of air from the turbine vent.

During the tests we measured the relative humidity and temperature inside the dryer and at the exhaust air outlet. Details will be summarized later but the interior temperature ranged 12 to 15 degrees F warmer than ambient air. Exhaust temperature was 5 degrees higher, probably due to the position of the thermometer near the center of the roof.

In other observations, at least with sweet potato the degree of dryness could be estimated by the color of the fruit. When fresh the fruit was a deep orange color, and as the fruit dried the color became much lighter. This rough test probably would not work for breadfruit.

We also tested dryness by bending the shreds. When wet, the shreds would bend, and when dry, would snap audibly.

We selected a subsample as a control, and dried that out in the open sunlight.

We selected a second sample and dried it using fuel as an assist, to test the hybrid capability. Results are summarized below.

b. Results

Due to the short time frame available for testing, detailed test readings will have to be provided at a later date. Nonetheless results are summarized here. (Note: See Appendix V added August 2015.)

For the first sample, testing spread over 2½ days. Drying was complete at the end of that time, much longer than hoped for, although conditions were not ideal. The first full sample weighed 3,875 grams fresh, and 720 grams when dried, for a reduction of 81 percent. We believe this result is optimistic due to the loss of tiny fragments through the screen. A rough estimate of the loss is 5 percent, which would change the drying reduction to 80 percent. This is a good result but needs to be replicated. Perhaps sweet potato has a higher moisture content than we estimated.

The control sample (a subset of the first sample) weighed 150 grams fresh, and 45 grams when dried, for a reduction of 70 percent. This result is what we expected but somewhat contradictory to the main test result, because in fact the open sun dried fruit appeared visually to be drier. Perhaps the sunlight bleached the color somewhat.

Although these results must be regarded as approximate, clearly substantial drying was accomplished and we view the test as quite successful, especially under the unfavorable test conditions.

Limited additional testing was performed using the heater. The heater raised the interior temperature 22 to 25 degrees F above ambient temperature. Exhaust air was 4 to 5 degrees higher. The rate of drying was subjectively observed to be much more rapid, but testing was not fully complete within 3 hours.

8. Design alternatives

This prototype has worked effectively to the extent described above. Weather conditions limited the extent of testing, so we concede that more testing is necessary.

We also have considered a number of design alternatives that could potentially improve performance of the design.

a. Larger collectors; with three collectors as described plus the front opening, there is a total of approximately 7 square meters of solar radiation collected. Typically at sea level solar insolation approximates 1.0 kW/m^2 giving a theoretical maximum heat collected of 7.0 kW. Larger collectors would increase heating power.
b. The design permits ganging of two or more cabinets side by side. This would increase production capacity but would mean less collector area for each cabinet. If two or more cabinets are ganged, it may be necessary to build larger collectors. This has not been tested.
c. If the collectors sloped more steeply (approximately 18 degrees, for Jamaica), especially the corrugated metal surface, there would be a slight increase in collected insolation as there would be less cosine effect.

d. The cabinet needs to be tightly sealed to avoid ambient air at lower temperature and higher humidity to leak in, and also to exclude insects.
e. The current cabinet design is square, for simplicity of construction. Air movement in the corners however is slower than nearer the middle. The shelf could be modified in shape, or at least should not be loaded with fruit all the way into the corners.
f. We considered the use of internal baffles to disperse warm air more evenly within the cabinet. This seems most important if fuel is being used, to avoid a hot spot directly above the heat, with inadequate drying around the center.
g. A chimney several feet tall may be a superior alternative to the solar exhaust fan.

The existing design meets the criteria of effectiveness, simplicity of construction, and relatively low cost. The design alternative above may further improve effectiveness at the expense of the other criteria. And of course many other designs are possible.

9. Deployment

The initial prototype has been built in Chicago and subjected to partial testing. Additional testing will be completed during the summer months of 2015. Providing the results continue to look good, a second prototype will be built in a warmer location (Jamaica or Haiti). Funding for this will be available. A structured testing program will be used and reviewed by a peer group. There may be desing modifications at this stage of prototyping.

If the capacity and costs are acceptable, the plan is to draw up detailed construction plans, with the aid of Northwestern University's Engineering Department, and to engage a construction company in the Caribbean to build some number of kits that may be easily shipped to various locations for assembly and use locally, near the sites where fresh breadfruit is available. The kits will be sold or donated as funding is available, to commercial users, co-ops or individual fruit producers. The intent is to stimulate the local market.

END

ACKNOWLEDGMENTS

We wish to thank many designers and supporters who have gone before us. In particular, Dr. Camille George of University of St. Thomas, Minnesota, introduced us years ago to drying experiments she conducted in Puerto Rico.

The collection of numerous cultivars all over Oceania was a stellar accomplishment of Dr. Diane Ragone, of Hawaii's Breadfruit Institute, a unit of the National Tropical Botanic Gardens.

Thanks also go to Dr. Stacy Benjamin and the faculty and students of the Engineering Department of Northwestern University, Evanston, Illinois, who built earlier prototype dryers.

And thanks also go to many others, who provided encouragement, advice and many forms of support.

APPENDIX I

COST OF PROTOTYPE DRYER

MATERIALS

Qty	Description	Unit Price	Total
7	Sheets of 3/8" marine plywood	25	175
6	2x4 pressure treated lumber 8'	4	24
22	2x2 pressure treated lumber 8'	4	88
8	1x2 pressure treated lumber 8'	2	16
7	Clear plastic sheet (collector cover)	25	175
6	Sheet metal 30 gauge (2 per collector)	14	84
2	Sheet metal for roof	16	32
4	Stainless steel for shelf	60	240
1	Mosquito netting	10	10
1	Solar exhaust fan	64	64
1	Turbine exhaust vent	38	38
1	Screws, fasteners, handles	60	60
1	Black paint	10	10
1	Kerosene or propane stove	50	50
TOTAL			1066

LABOR

30	Hours	20	600

TOTAL 1666

Not included are one time costs such as the humidity and temperature gauges used in testing. Also not listed above are several much lower cost alternatives, for example to the sheet metal, stainless steel and less expensive lumber.

APPENDIX II

TEMPERATURE AND MOISTURE HOLDING CAPACITY OF AIR

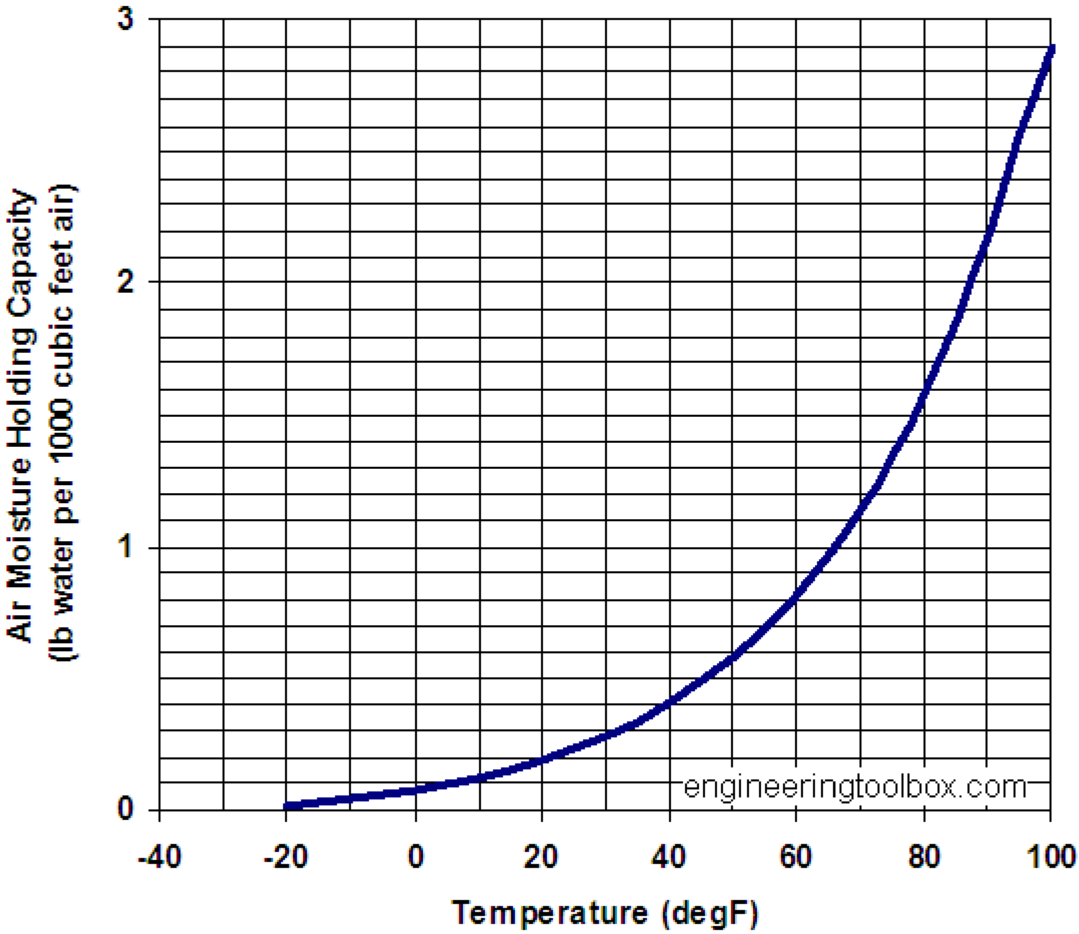


Chart presented courtesy of engineeringtoolbox.com.

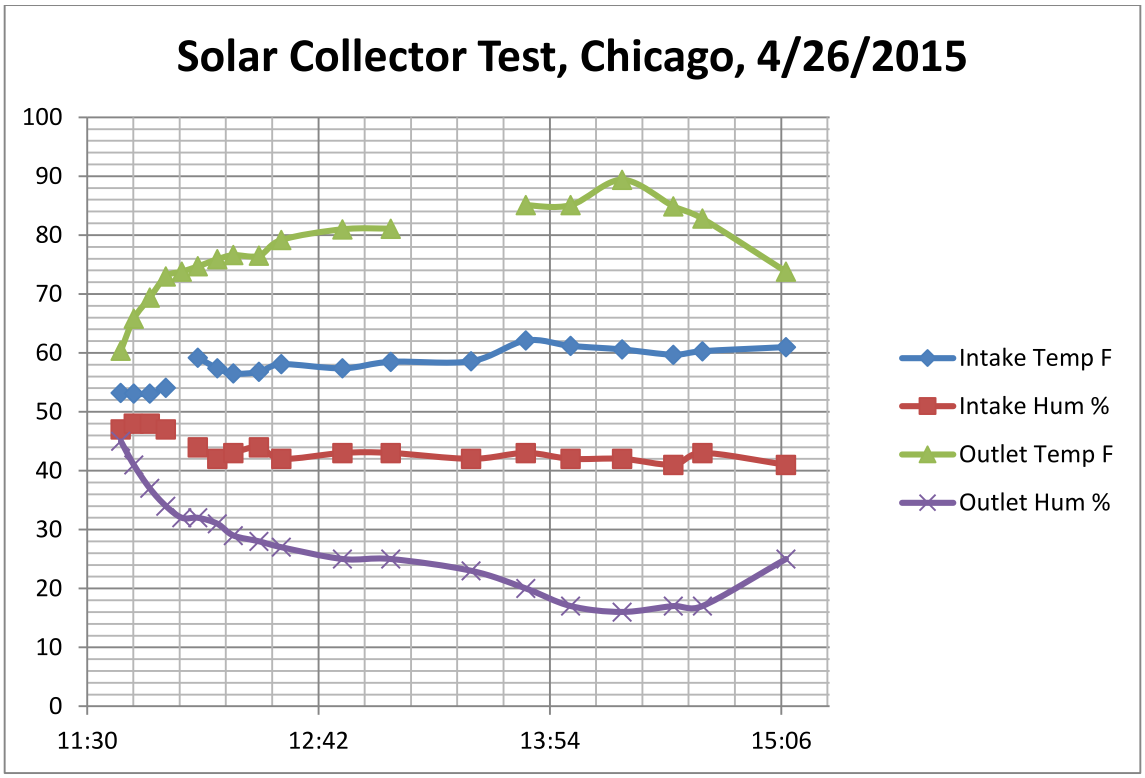
At 100 degrees F, air holds approximately 3 pounds of water per 1,000 cubic feet. In an ideal situation, removal of 70 pounds of water from 100 pounds of fresh breadfruit would require 23.33 thousand cubic feet (MCF) of dry air. More realistically, given that ambient air already contains moisture, and given the uncertainties around other conditions, it was estimated that 80 MCF of air flow would be needed. The exhaust fans will extract an estimate 500 cubic feet per minute (CFM) indicating that complete drying would require 80/0.5 or 160 minutes, or about 3 hours. Further testing is needed to confirm.

An alternate calculation below is taken from Professor Xiandong's paper. With incoming air at 20 degrees C, and exiting at 80 percent relative humidity, the moisture absorbing capacity is shown for different initial relative humidities and heated to different levels. If the units are converted, the table indicates that we should expect removal of approximately 1 pound of moisture per thousand cubic feet. These results are consistent with the above, namely 70,000 CF to dry 100 pounds of breadfruit.

Initial relative humidity	Moisture absorption capability (grams of water per m^3 of air [g/m^3])		
	Not heated	Heated to 40°C	Heated to 60 °C
40%	4.3	9.2	16.3
60%	1.4	8.2	15.6
80%	0.0	7.1	14.9

APPENDIX III

Preliminary Testing



Temperature is shown in degrees Fahrenheit. Time of day is Central Daylight Time in the Chicago area.

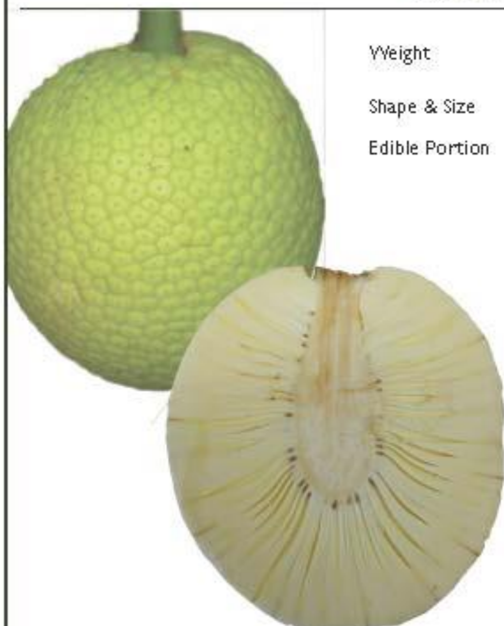
Data readings are shown below.

	Intake		Outlet	
time	Temp F	Hum %	Temp F	Hum %
11:37				
11:41	53.2	47	60.4	45
11:45	53.1	48	65.8	41
11:50	53.1	48	69.4	37
11:55	54.1	47	73	34
12:00			73.8	32
12:05	59.2	44	74.7	32
12:11	57.4	42	75.9	31
12:16	56.5	43	76.6	29
12:24	56.8	44	76.5	28
12:31	58.1	42	79.2	27
12:50	57.4	43	81	25
13:05	58.5	43	81.1	25
13:30	58.6	42		23
13:47	62.1	43	85.1	20
14:01	61.2	42	85.1	17
14:17	60.6	42	89.4	16
14:33	59.7	41	84.9	17
14:42	60.3	43	82.8	17
15:08	61	41	73.8	25

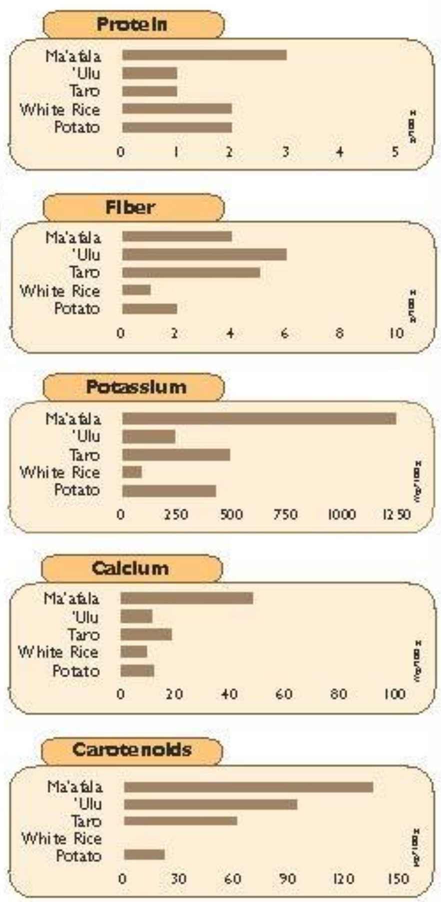
APPENDIX IV

NUTRITION INFORMATION

MA'AFALA



Weight	1.4 - 2.3 lbs (634-1053 g) 1.7 lbs (783g) average
Shape & Size	Oval; 5-6" long x 4-5" wide
Edible Portion	83%



Ma'afala produces 150-200, or more, delicious, nutritious fruits per year. The fruit has a creamy to pale yellow flesh and is usually seedless. The flesh has a soft, tender texture when cooked.

Breadfruit is a starchy energy-rich carbohydrate food and is also gluten free. Ma'afala is higher in protein (3.3%) than most breadfruit varieties, and flour made from the dried fruit contains 7.6% protein. It is a good source of fiber and rich in minerals such as potassium, magnesium, and calcium. Ma'afala also provides niacin, thiamin, and riboflavin (B vitamins), Vitamin C, and Vitamin-A producing carotenoids.

BREADFRUIT INSTITUTE - NATIONAL TROPICAL BOTANICAL GARDEN
www.breadfruit.org

Courtesy of the Breadfruit Institute of the National Tropical Botanic Garden

APPENDIX V

FIELD TESTING OF HYBRID SOLAR DRYER

S M McLaughlin

		AMBIENT		INTERIOR		EXHAUST		
DATE	TIME	R H A	Temp A	R H In	Temp In	R H Ex	Temp Ex	OBSERVATIONS
7/2/2015	10:32	59						
	10:38	59	66.6	61	75.6	52	78.2	
	10:46	64	64.0	59	76.7	48	81.9	
	10:55	67	63.3	57	76.5	47	79.7	
	11:20	67	64.6	59	75.0	50	78.4	shade falling on collector
	12:02	66	65.3	52	80.4	48	81.1	turbine turning v. slowly
	12:22	66	65.7	51	81.0	45	82.0	hazy sunlight
	13:07	65	66.0	48	80.8	43	85.1	hazy sunlight
	13:53	65	66.0	48	79.2	47	80.8	hazy sunlight
	14:21	64	65.8	49	78.1	47	79.3	hazy sunlight
	14:48	64	66.2	47	79.2	47	79.3	hazy sunlight
	15:19	64	66.6	47	79.2	46	80.2	hazy sunlight
	16:27	64	66.2	48	77.0	48	77.2	fruit still wet, cold
7/3/2015	11:10	74	70.9	50	84.0			shreds hard to spread evenly
	11:25	72	71.6	49	84.7	39	89.2	hazy sunlight
	12:00	66	72.7	49	82.6	42	87.8	hazy sunlight
	12:30	69	72.3	48	83.7	41	89.1	turbine turning v slowly
	13:09	64	73.8	45	86.9	39	89.8	turbine a bit faster
	13:53	64	73.9	45	86.5	37		edges dry; zinc sheet hot to touch
	15:04	61	74.1	42	86.7	37	90.5	full sun
	15:42	60	75.0	42	86.7	35	91.8	shelf mesh may be restricting air flow
	16:38	57	75.2	42	82.8	37	86.0	
7/4/2015	11:21	60	76.5	41	90.1	30	95.4	hazy sunlight
	11:42	60	77.2	41	90.5	30	95.9	no wind
	12:12	59	78.4	39	96.8	27	101.3	heater turned on
	12:37	55	78.6	29	103.5	21	108.0	stronger wind; turbine spinning faster
	13:18	54	79.7	26	103.6	17	113.2	cabinet leaky to air
	14:09	51	80.8	24	103.1	14	109.2	tiny shreds falling through mesh

RH = Relative Humidity

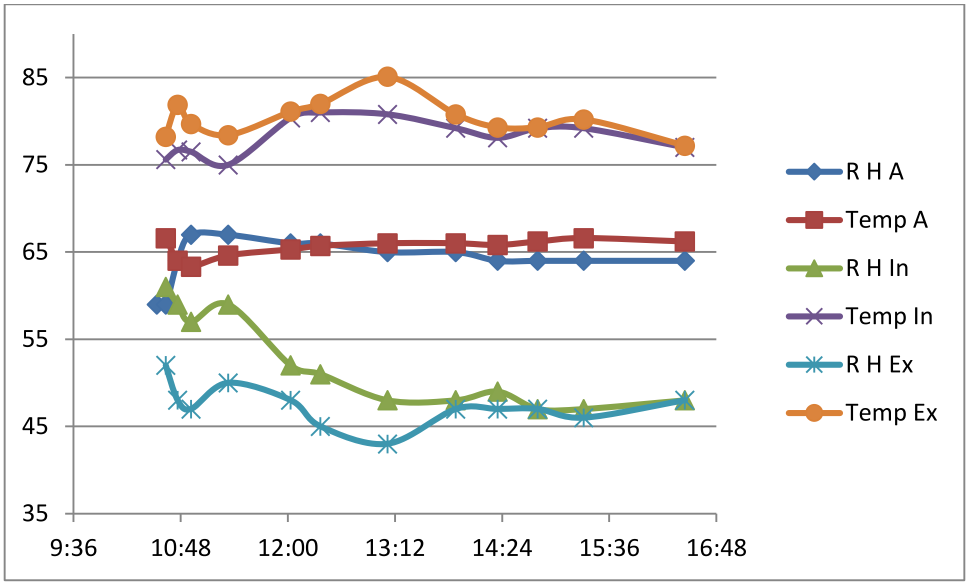
Ambient = surrounding humidity and temperature

Interior = measurements inside cabinet

Exhaust = measurements at exhaust fan atop cabinet roof

APPENDIX V (Continued)

GRAPH OF VARIATIONS, JULY 2, 2015



Data from Table, Above

Vertical axis shows temperature in degrees Fahrenheit and Relative Humidity as a percent

Horizontal axis shows Central Daylight Time, July 2, 2015

About the Author

Mr. S. Michael McLaughlin is Jamaican by birth. Mike attended St. George's College High School, was a Jamaica Scholar, and a Physics major at University of the West Indies. Mike qualified as an actuary and left Jamaica for opportunities abroad. He has lived in Chicago, Illinois for 25 years. With his wife Mary, and Paul Virtue, they co-founded Trees That Feed Foundation, primarily to feed people by improving the availability of nutritious fruit from trees.

About Trees That Feed Foundation

That Feed Foundation's mission is planting trees to feed people, create jobs and benefit the environment. TTFF has provided over 65,000 fruit trees to the people of Jamaica, Haiti, and other countries. TTFF also provides training, equipment and other support, to ensure a profitable, sustainable marketplace.