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Capstone Design Subtopic

Design of a Solar Powered Fruit and Vegetable Drier

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Abstract

Current market research indicates the need for an economical solution to efficiently dehydrate fruit and vegetables in equatorial climates. This is especially true for the banana industry of Central America. The goal is to design a cost effective solar powered fruit and vegetable dehydrator. The proposed design accommodates five (5) pounds fruit or three (3) pounds of vegetables and can remove seventy-five (75) percent of the water content in less than six (6) hours. This design is portable and robust enough to withstand the outdoor elements of equatorial climates. Using thermodynamic, heat transfer, and mass flow analyses, it has been shown that on an average day in this climate the dehydrator can achieve temperatures upwards of 120 °F. The design as tested consists of a clear acrylic dome top, solar powered exhaust fan, mesh drying rack, blackened aluminum base and a series of wire mesh acting as a heat exchanger. The fruit dehydrator has been successfully designed at a mass production cost of \$48.12 per unit.



Introduction

The concept of fruit drying employing the sun's energy is not a new idea however it has not yet realized its full potential. The benefits of dehydrating fruits and vegetables are immeasurable. One such benefit is that dehydrated fruit weighs only an eighth as much as its fresh counterpart. Dried foods can be made from lower quality fruits and vegetables that might otherwise be wasted. If kept cool and dry after dehydration, the product will remain edible for several months.

As a rule, products which employ solar drying techniques are relatively cheap, however the labor involved in handling these crops is often quite expensive in comparison. As a result, the added expense of implementing solar based equipment is not usually an option. There must be some benefit to the customer financially to make it feasible to use solar devices. These benefits could range from increased speed of drying in units of limited capacity to improving the quality of the product.

There are many factors to consider when creating a comprehensive prototype. Some of the major concerns are eliminating moisture, not overheating the fruit, and the durability of the unit. Since the device will be used outdoors and exposed to harsh climates with high temperature conditions, superior durability in the design must be incorporated. The sun's power in the regions of use is very intense and over-drying or cooking the fruit is a potential problem.

To aid in the optimization of this design, it proves beneficial to select a certain region in order to focus the research and design constraints. Equatorial climates are ideal for fruit dehydration as a result of the intensity of the sun's radiation in these regions. For design analysis and simulated environment testing, the country of Guatemala was chosen, as it is a mere 14 degrees north of the equator. Since Guatemala is a primarily agricultural economy, its leading commercial export comes from the cultivation of bananas. In 2002, Guatemala cultivated 1 million metric tons of bananas. These factors make it an easy choice as a region of focus. Since the period of time for which bananas are still fit for

human consumption is limited, drying the fruit allows for long time storage. Where bananas are farmed in Guatemala, electricity is not always available; therefore, there is a great need for a fully solar powered dehydrator.

Processing Fruit

Dehydration of fruits and vegetables is one of the oldest forms of food preservation techniques. Preservation is the main reason for dehydration, but not the only one. Dehydration is also used to lower the cost of packaging, storing and transportation by reducing the weight and volume of the final product. Also, people enjoy dried fruits as a healthy and nutritious snack.

Dried or dehydrated fruits and vegetables undergo the following process steps: pre-drying treatments (i.e., size selection, peeling, and color preservation), drying, and post-dehydration treatments (i.e., sweating, inspection, and packaging). There are many techniques that one can consider after the drying process has been completed. For example, one process called conditioning consists of leaving the fruit in open air for long periods of time to allow it to equalize the moisture content. Another practice which will help fruit keep for extended periods of time is pasteurization. During pasteurization the fruit is exposed to very high heat to eliminate harmful bacteria and organisms. The first two steps will be focused on due to the designs intended use.

In order to focus the calculations and design, it is desirable to select a specific fruit and region. It was decided that bananas would be the fruit that this project would be based on. Bananas are a well known dried fruit, and the simplicity of acquiring and processing bananas make it a very desirable raw material. Also, it is the number one commercial export from Guatemala. Another reason that bananas make an ideal fruit to dehydrate is their small drying times. The NESCO[®] Snackmaster[™] Instruction Manual shows that

bananas only take 6-8 hours to dry, whereas fruits such as apples and pineapples take 6 hours and 10 hours to dry, respectively.

Pre-drying treatments

Pre-drying treatments include raw material preparation and color preservation. Raw material preparation includes selection, washing, peeling, cutting, and blanching (mainly for vegetables). The fruit or vegetable is selected according to size and ripeness and then washed to remove any unwanted matter on the outside of the product. The product can then be peeled by hand, with lye, with an alkali solution, with dry caustic or mild abrasion, with steam pressure, with high-pressure washers, or with flame peelers. Peeling is usually reserved for apples, pears, bananas, pineapples, carrots, beets, parsnips, potatoes, onions, and garlic.

Next, the product is cut into its appropriate form. For bananas this consists of cutting the banana into roughly 1/8" thick slices to be spread evenly across the drying surface. This speeds up the drying process, and enables the bananas to be dried in the popular "banana chip" form.

Next is the treatment of the fruit or vegetables with chemicals for color preservation. For most fruits this consists of treating them with sulfur dioxide for its antioxidant and preservative effects. Sulfur dioxide is extremely effective in slowing the browning of fruits. This chemical also reduces the destruction of carotene and ascorbic acid, two essential nutrients in fruits. Color preservation for vegetables involves sulfite solutions. The sulfite allows better storage conditions and makes it possible to increase the drying temperature, allowing a decrease in drying time.

Since this product is going to be marketed to areas such as Guatemala and other tropical regions, the decision was made to disregard the use of pre-drying treatments. The use of chemicals is an unnecessary added expense to the drying process. For drying purposes alone, no preservation chemicals are needed.

Drying

There are two main factors in the drying process. The first factor is the fruit's contact with direct radiation. Solar radiation, mostly in the infrared spectrum, directly heats the fruit and can increase the temperature just under the surface by as much as 46° F. The second method, known as indirect heating, is achieved by subjecting the fruit to a stream of hot air. By increasing the internal temperature of the dehydrator, one increases the vapor pressure of the water. This hot air can penetrate the pores and accelerate the removal of moisture. The more porous the fruit is, the quicker the removal of moisture will be. However this evaporation will have a cooling effect thus slowing the flow of heat into the fruit.

In order for a banana to be considered "dried," its moisture content must be no greater than 25%. An ideal dry banana chip contains between 30-40% of its original mass. On average, a fresh banana has initial moisture content in the range of 75-80%. This means that about two-thirds of a banana's moisture must be removed in order for it to be "dried." 2 BTU's are necessary for each gallon of water removed from the bananas. A steady state of water evaporation will occur when the heat required for evaporation and the heat losses from the system combine to equal the total heat absorbed.

The two main drying procedures looked at are sun and solar drying. Sun drying is used almost exclusively for fruits. It is limited to climates with high heat and low humidity. This procedure involves having the fruit be sun-dried by simply spreading the fruit on the ground, racks, trays, or roofs and exposing them to direct sunlight until dry. The advantages to this idea are its simplicity and its small capital investment. The disadvantages include a complete dependence on the elements and humidity levels no higher than 15 to 20 percent. Solar drying is generally the same as sun drying, except it

utilizes black-painted trays, solar trays, collectors, and mirrors to increase solar energy and accelerate drying.

Patent Search

Before designing our fruit drier a patent search was performed in order to determine the previous products on the market. There are approximately eight (8) patents which are related to the design of a solar powered fruit and vegetable drier. The patents date back as far as 1923 and as recently as February 10, 2004. Three similar patents which have been investigated in order to ensure that there is no infringement upon design rights include: Anrassy's U.S. Pat. No. 5,001,846 (1991), O'Hare's U.S. Pat. No. 4,501,074 (1978), and Muller's U.S. Pat. No. 1,556,865 (1923).

Anrassy's patent, seen in Figure 1 below, consists of a solar drying apparatus with a translucent sloping top and means for evacuating the condensation from the moist air. The specification describes a perforated or porous tray on which the materials are arranged for drying. A solar powered fan forces drying air vertically through the porous tray.

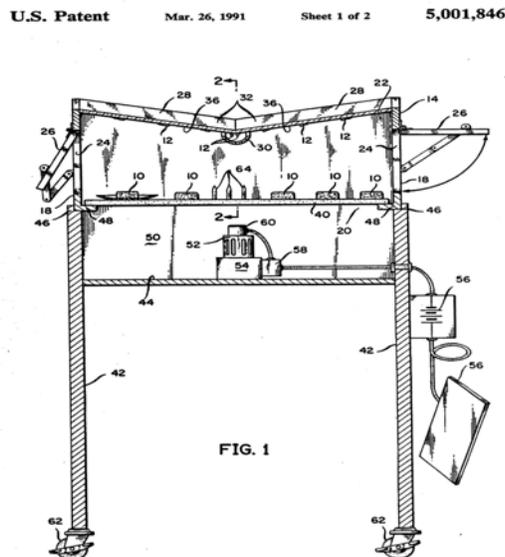


Figure 1: Anrassy's Patent

O'Hare's patent, Figure 2, consists of a convection powered solar food dryer that discloses a solar collector on the inlet side for heating intake air, and a vertical solar tower or column to accelerate the convection of warm air through the system by suction. The actual drying chamber can be removed from the solar devices at each end of the convection system. The materials are arranged on shelves in the drying chamber.

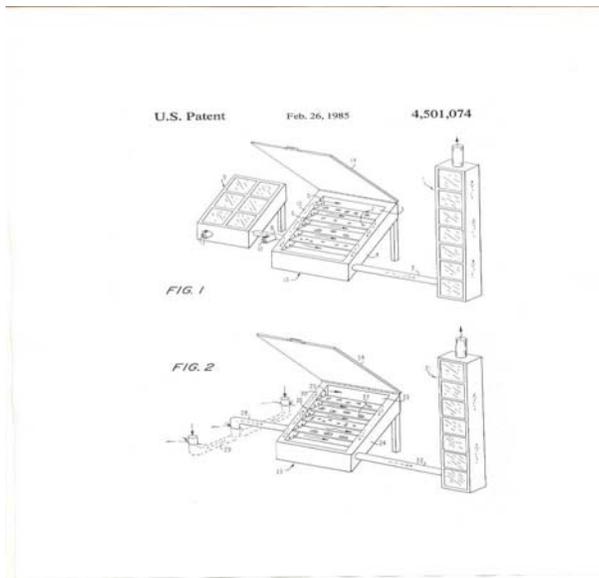


Figure 2: O'Hare's Patent

Muller's Patent, Figure 3, consists of a solar powered dryer system for vegetable matter, consisting of a series of circumferential racks with inlet perforations in the sidewalls and internal shelf brackets in the corners for holding drying shelves or trays. The racks are configured for interlocking stacking underneath a solar collector roof which has a central exhaust vent.

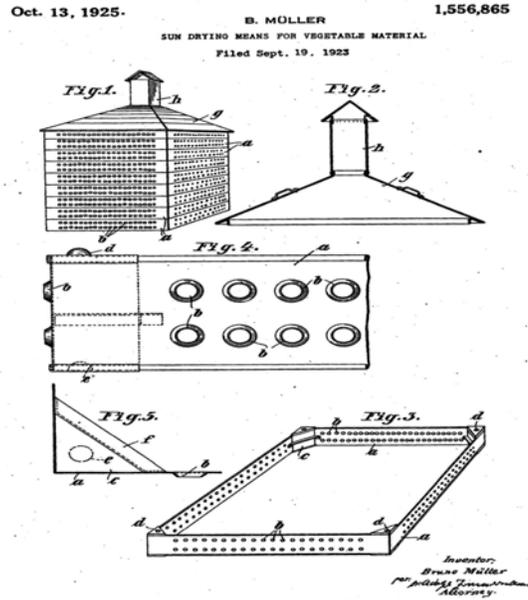


Figure 3: Muller's Patent

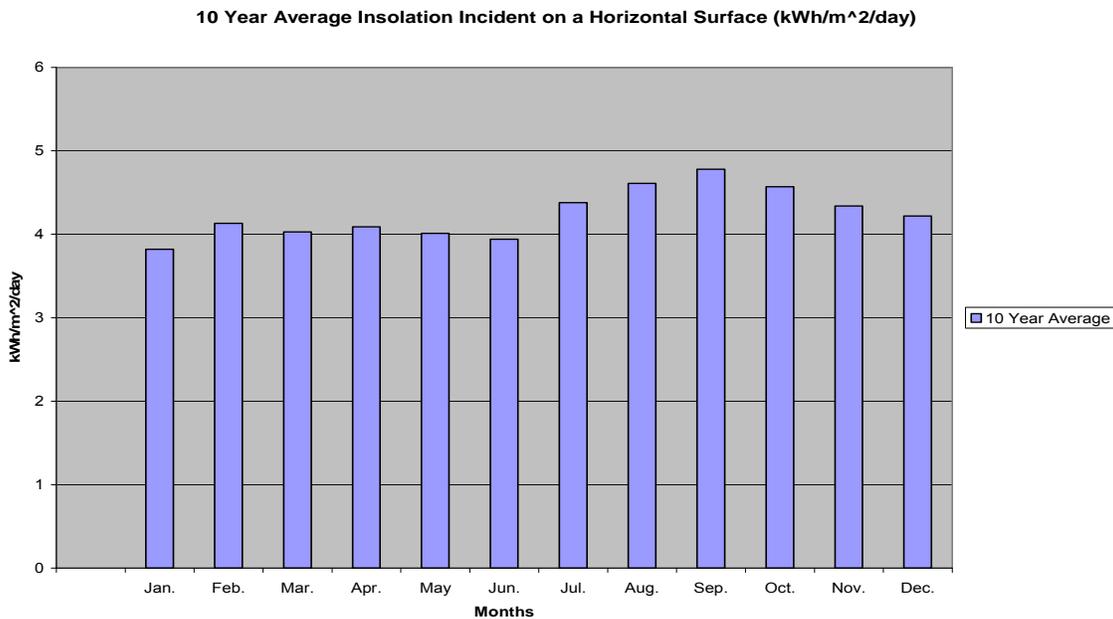
Guatemalan Atmospheric Data

Preliminary data research was conducted through the NASA Surface meteorology and Solar Energy Regional/Global Database. This database contained 10 year monthly averages for a wide variety of data which is pivotal to the design of the fruit drier. The meteorology data collected that will be used includes average % Relative Humidity, average atmospheric pressure, average air temperature, average air temperatures in 3 hour increments, cooling degree days, and heating degree days. Solar Energy data collected includes insolation incident on a horizontal surface, midday insolation incident on a horizontal surface, clear sky insolation incident on a horizontal surface, and average daylight hours. Graphs and charts of the data collected can be found in Appendix A.

Two of the most important factors are relative humidity and solar insolation. Relative Humidity is defined as the ratio of the mole fraction of water vapor in a given moist air sample to the mole fraction in a saturated moist air sample at the same mixture temperature and pressure¹. In order to efficiently dry fruit and vegetables, water has to be removed from the fruit and then the moist air must be pulled out of the drying chamber

and replaced with fresh, drier outside air. Knowing the amount of water already in the air, the amount of heat generation and mass flow in the drier was calculated. The average relative humidity in Guatemala was found to have a range from 73.6% to 85.0%².

Solar insolation is the amount of energy received from the sun at the Earth's surface. The climate zones, seasonal temperature changes and daily temperature changes are largely controlled by changes in the amount of energy received by the sun due to changes in the angle at which solar radiation strikes the surface. These all affect the amount of energy received by the earth's surface from the sun. The data collected is measured in kWh/M²/day. The average solar insolation incident on a horizontal surface in Guatemala was found to have a range from 3.82 to 4.78² (see Graph 1 below).



Graph 1: Guatemala Annual Insolation Incident Data

Simulated Environment Design



Figure 4: Simulated Environment

In order to properly test the solar powered fruit and vegetable drier, an accurate simulation of the environment found in Guatemala was designed and constructed. Using the summer design loads from ASHREA standards and NASA weather and solar data, the appropriate environment is to be between 78-82°F dry bulb temperature and a relative humidity of 80-82% must be kept². Also, the NASA solar data for Guatemala shows the light output onto a horizontal surface area will be 500 W/m². Because the tests are performed indoors in a laboratory, the conditions must be mocked in a smaller test area within the lab. Typically, a classroom or lab during winter conditions is approximately 70-74°F and approximately 15-20% relative humidity.

The design requirements for the artificial environment include two (2) clear TeflonTM coated 250 watt infrared heat lamps to remain on at all times during testing. These lamps were chosen because they produce a wavelength or spectrum between 0.3 and 3 nanometers. The brains of the simulated environment are controlled through an Andover Controls i2 865 controller, which has four universal inputs, three triac-based outputs, and an integrated damper actuator. The attached Belimo damper actuator produces 35 in-lbs of torque to actuate a 18"x24" Johnson Controls balancing damper. The relative humidity input comes from a Veris Industries HW series wall mount sensor rated at 5% accuracy. Accompanied with the Veris RH sensor is an Andover Controls Infinity series

Smart Sensor LCD display temperature sensor. The Smart Sensor is accurate to within +/- 0.36°F and displays icons for when the humidifier and fan are operating. The i2 865 controller sends a 24VAC signal to two separate Functional Devices RIB single pole double throw relays with LED on light to operate the fan and humidifier on or off. Utilizing a Holmes electric fan and an Air King® reticulating humidifier, the simulated environment is kept to within the design requirements and is an exceptional representative of the Guatemalan climate. All product sheets, point-to-point wiring diagram, and sequence of operations can be found in the appendix.

Current Products on the Market

There are many non-commercial fruit, vegetable, and jerky dehydrators on the market. Currently, most of the technology for personal fruit and vegetable dehydration is limited to a typical 120V a.c. electric powered fan with a 500 watt heating element of drying power, which can provide a temperature range of 95°-165° F. These dehydrators are capable of drying foods in just hours, unlike natural outdoor drying which could take days. These sleek designs are seen in many large markets and/or specialty food stores selling anywhere for \$39.99 for a 12 shelf, 11 ft² drying surface manufactured by Snackmaster ranging up to \$259 for a stainless steel dehydrator with a 10 shelf, 16 ft² drying surface by TSM.

Because these designs are powered by conventional electricity, they fail the criteria for a purely solar powered fruit and vegetable dehydrator. The only purely solar powered fruit and vegetable dehydrator capable of using the power of the sun and solar technology to dry food within a reasonable time is manufactured and marketed through Environmental Solar Systems based out of Methuen, MA. Their non-patented product, called the Natural Food Dehydrator (*See Figure 5*), uses the sun's direct heat rays to penetrate through the transparent cover. Using natural ventilation, with no solar cells needed, on opposite sides of the tray, it creates a warm current across the stainless steel food tray. The single tray is 22"x44" which is almost 6.75 ft² of drying area. But, because it is a non-expandable design, it does not allow for multiple shelves under a single housing. At the costly \$309 list price, this product would not be feasible for any fruit and vegetable

growing farmer or homeowner. A farmer or homeowner may purchase a commercial size Natural Solar Food Dehydrator, increasing the drying area over 260% to almost 18 ft², but paying \$549. There is no low cost, fully solar powered, food dehydrator on the market at this time. In areas where there is no electricity, the options for fast food drying are limited and open air drying is the only solution.



Figure 5: Environmental Solar Systems – Natural Food Dehydrator

Design Considerations



Figure 6: Basic Design of Enclosed Drying Container

Fruit dehydration is carried out at a temperature which does not greatly exceed the ambient air; as a result, it is not necessary to have an elaborate solar collector. A solar collector is a unique type of heat exchanger which transforms solar radiant energy into heat. Solar collectors vary in many respects to more conventional heat exchangers. In a heat exchanger, the transfer of energy occurs at a fluid-to-fluid interface at a very high rate, thus rendering radiation unimportant. On the other hand, solar collectors use a distant source of radiation, the sun, and transfer it to a fluid. The maximum flux of the sun's incident radiation is 1100 W/m^2 and is highly variable. The wavelength range of the sun's radiation is in the range of $.3 - 3 \mu\text{m}$. This is considerably shorter than the energy emitted by most energy absorbing surfaces.³

This design is based on the flat plate collector (FPC) theory. There are many benefits to this type of design. Perhaps the most significant advantage is a result of the fact that flat plate collectors can use both beam and diffuse radiation, thus allowing them to operate on bright cloudy days. Beam radiation is defined as radiation received from the sun

without having been scattered by the atmosphere. Conversely, diffuse radiation is the energy received from the sun after its direction has been changed by scattering in the atmosphere. This ability to employ both diffuse and direct radiation eliminates the need for extensive tracking of the sun. Flat plate collectors have an operating limit at approximately 200° F above ambient temperature, making it perfect for the dehydration of fruit which occurs at ~100° F above ambient. Other benefits include the relative mechanical simplicity of design as compared to many other solar collectors and the lack of required maintenance.⁴

The physical properties of the fruit to be dried are needed to determine the appropriate size of the collector. Since there is an abundance of types of fruit, it is beneficial to focus on one: bananas. The average weight of an unpeeled banana is approximately 4.75 ounces and a mere 4.16 ounces peeled. The length is slightly more complicated. The average length of a banana is 8 inches. This measurement is the external total length including the stem and butt end. Once the peel and the unusable ends have been removed the average working length becomes 5 inches. The average diameter of this section is 1.25 inches. In order to make banana chips, the ideal thickness of each slice is 1/8” thick.⁸

Transparent Dome Cover

The purpose of a transparent media on the top of a solar collector is to trap the heat inside. The two most logical choices are glass or a transparent plastic. There are many considerations which must be taken into account when selecting a material to use in a solar collector. These factors include the ability to withstand rain and dust, the influence of temperature on the deterioration of the material, warping as a result of the temperature gradient, and the loss of transparency (both visible and non-visible). The major considerations for all transparent media are the same. The transmission of light through plastic depends on the refractive index of the material and the reflections at the *two* air-plastic interfaces. There are two interfaces as a result of the two surfaces on both sides of

the panel that the beam must pass through. Absorption of energy in plastics is generally less than that of glass. This is a result of the ability of plastics to be thinner than glass.

Glass has been used extensively as a cover for solar collector for decades. There are many benefits to using glass, but perhaps the most compelling is the fact that it is very resilient to harsh environments. On the other hand it is very heavy and fragile, thus requiring robust structures to support it. Glass is transparent to most of the elements of sunlight, excluding only ultraviolet. It is opaque in the longer infrared spectrum, thus proving to be a very effective heat trap. The reflection at each interface of glass and air is approximately 4%, while the absorption of the glass itself may be in the range of 5-6% or more depending on the iron content. When these factors are combined, it is estimated that the overall transmission is reduced by at least 10% each time light passes through a sheet of glass.⁴

The advances in plastics have been phenomenal in recent years. These advances are so concrete that the employment of glass in solar collectors is becoming obsolete. Plastic outperforms glass in many areas including strength, resiliency and lesser density. The overhead costs associated with designs using plastics are fractional when compared to that of glass. There are concerns with using plastic for solar collectors. Sunlight and weathering will deteriorate materials establishing them as the two major deterrents in selecting plastic.

Acrylic plastics transmit and control light, resist weather, and are stable against deterioration. Transparency, gloss, and dimensional stability of acrylics are virtually unaffected by years of exposure to the elements, salt spray, or corrosive atmospheres. They also combine structural and thermal properties, making them very appropriate for heat exchange applications. Clear acrylics are as clear as the most expensive optical glass, combining an index of refraction of 1.49 with 92% light transmittance.⁶

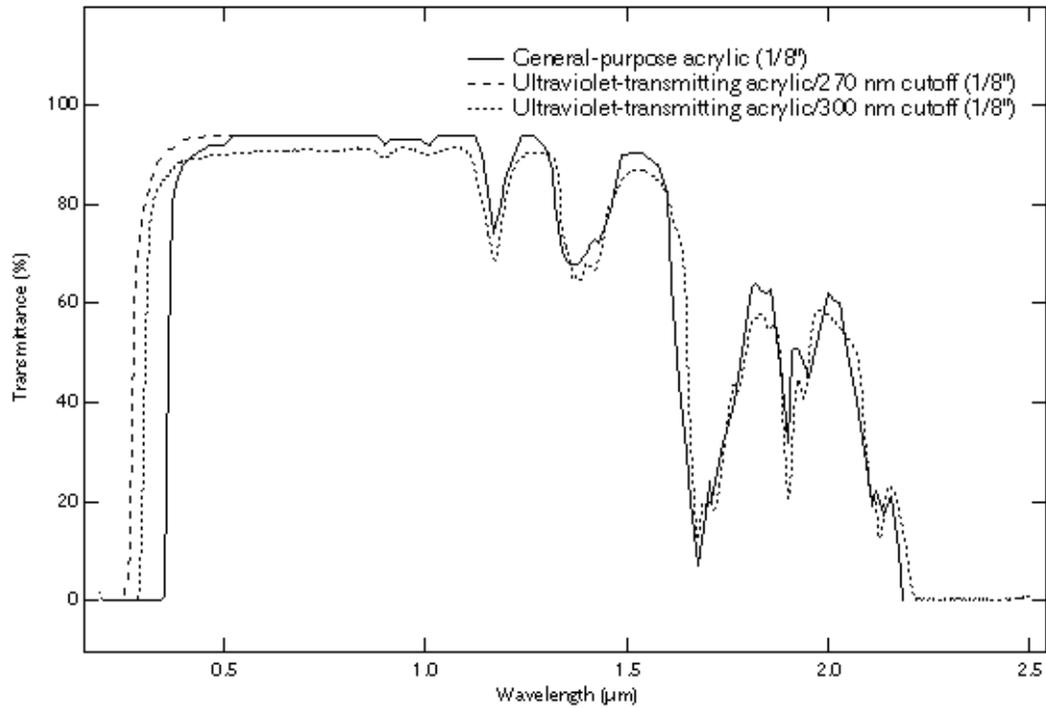


Figure 7: Transmission of Acrylic as a Function of Wavelength.⁷

As is apparent from the graph, acrylic has a very good transmittance in the visible and IR spectrum, which is where the bulk of solar energy is located. Acrylic lends itself very well to injection molding but is sometimes difficult to machine as a result of its high heat retention. This property is very desirable for solar collectors and by simply using ample amounts of water when machining this roadblock can be skirted. The dome should not require any machining when the design is finalized, reducing risks and overall cost. All of the technical aspects combined with the widespread availability make acrylic an excellent material selection for the collector cover.

With the selection of acrylic finalized, the next consideration is a physical geometry of the cover. Since the dehydrator will be fixed and not angled in a particular direction, it is desirable to absorb as much radiation as possible over a variety of conditions. When the sun is closer to the horizon, as it will be over the six hour drying time a flat plate will not necessarily collect enough energy. To do this, a vertical component of the collector must be created (See Figure 8). Once the radiation is inside the dome, it can only leave through another acrylic interface. This means that at least 8 percent of the radiation that

is attempting to leave the dome is reflected back into the system. This combined with the radiation that comes in contact with the fruit can give the dome up to a 15 percent advantage over a flat collector. In order to limit calculations for dehydrating times depending on the season and other factors, a geometry that is uniform at all angles is desired. Another consideration is the lack of seams that would be unavoidable if flat panels were used. All of these factors make a very strong case for the dome.

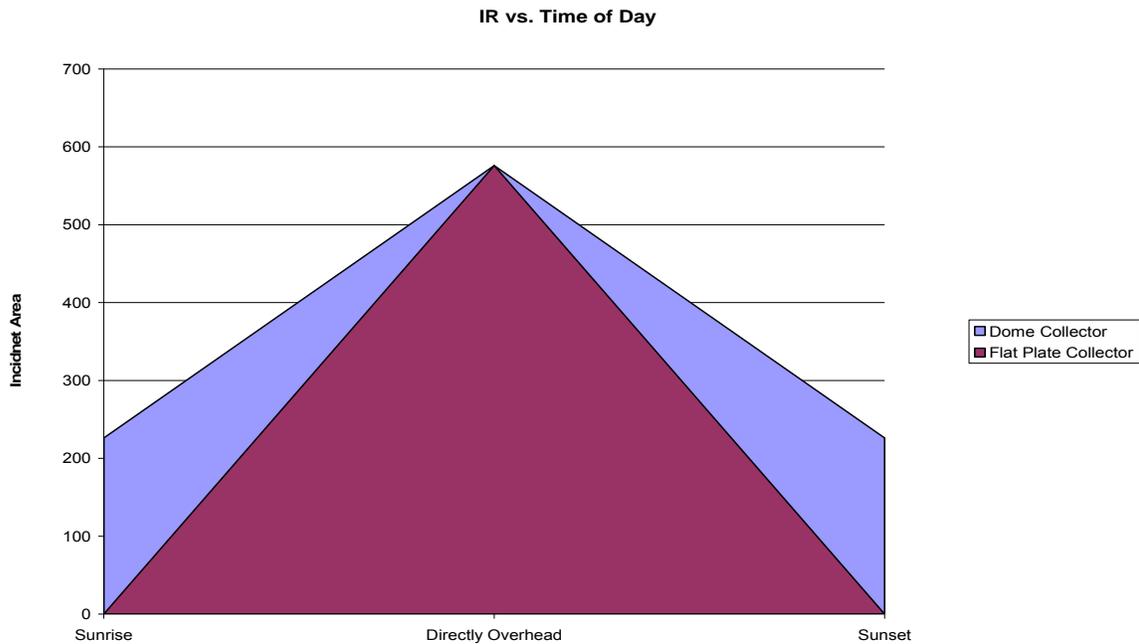


Figure 8: Plot showing the Incident Area as a function of the Time of day.

Base Design

The base of solar collectors should always be made of some form of metal. Typically sheet metal made of iron, copper, or aluminum is used as a result of their good conductive properties. As the metal base rises in temperature, it transfers heat to the air flowing through the vent holes in the base. The metal base will also waste heat to the surroundings by convection to the moving air currents, conduction to the air, and by infrared radiation. As solar radiation continues to strike the base, the temperature will rise, but the losses also increase until a steady state is reached. Aluminum has been

selected for this design for a number of reasons. The two major reasons are the price and ease of machining. Also aluminum has a high diffusivity which is desirable for heat transfer. In order to transfer heat and absorb all of the sun's energy which enters the system the aluminum base is blackened through anodizing.

The limited contact area is not enough to raise the energy of the air to the desired temperature. It is beneficial to have a sort of heat exchanger. Heat transfer is appreciably more when the flow turbulent, thus there must be some method for establishing a turbulent flow is the heat exchanger. Wire mesh is often used to create turbulent flow. If this mesh is black it will also absorb the solar radiation. The number of meshes can be increased to create more heat transfer. Also, it makes it possible to absorb every ray of solar energy.

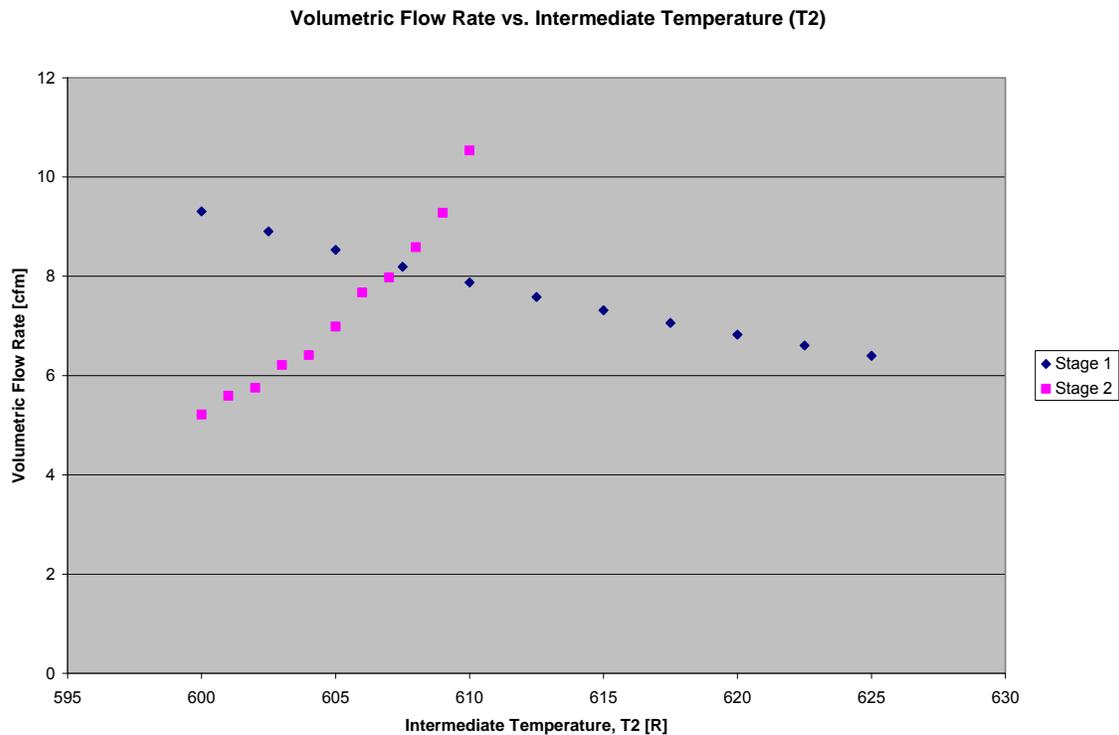
One of the key design goals is that the dehydrator must be portable. Using the industry data on average banana sizes, it is calculated that an area of 4 sq. ft is needed to dry the desired 5 lbs. This size is easily manageable for one person.

Optimization and the Steady State

The analysis included in this report can be divided into three distinct parts. A heat transfer analysis is the most important and yields the steady state temperatures of different system components. Once these temperatures are known a psychometric analysis is done to determine different important parameters such as relative humidity. The last important part of the analysis is a mass diffusion problem. Once the temperatures of the different components are determined, the relative humidity is known and with the help of experimental data, a drying time for a given quantity of bananas can be calculated.

When a solar collector, such as a solar fruit dehydrator, is exposed to solar radiation its temperature will increase until equilibrium is reached. In other words, it will maintain a steady state when the thermal gains are equal to the losses. The major sources of loss are the emission of radiation and convection from the heated surfaces to the surrounding cooler air. The gains are more apparent and somewhat easier to quantify. They are a direct result of the intensity of the solar radiation and the quantity of radiation collected by the surfaces of the dehydrator.

An energy balance analysis consisted of two systems in steady state. The first system being the heat exchanger region (base to wire mesh) and the second being the drying area (wire mesh to exhaust fan). The regions were analyzed and the exit temperature of system one was compared to the inlet temperature of system two. The region where the two systems had equal temperatures was determined and the mass flow rate for the entire system was obtained.



Graph 2 – Volumetric Flow Rate vs. T₂

The steady state temperatures of each individual component of the system can be calculated by thermal circuit analysis. Below is an illustration of the circuit used for this analysis. It consists of thirty equations and thirty unknowns. However the circuit only yielded twenty five equations so the five incoming heat flows had to be approximated using different known system parameters.

Thermal Circuit

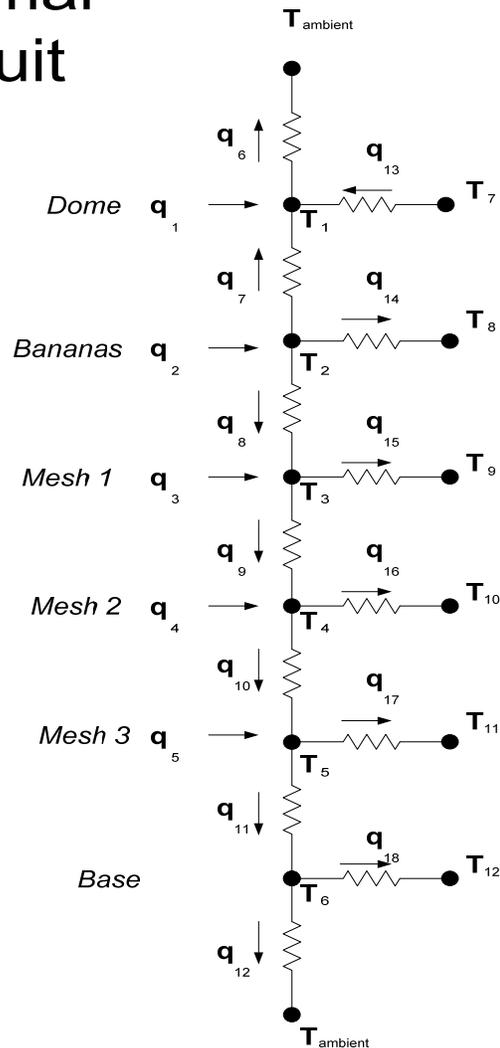


Figure 9: Thermal Circuit

This thermal circuit is a good representation of the fruit dehydrator because it accurately represents the different stages that the air travels across. The air comes in at the bottom through the base, goes through several fine wire meshes (which act as a heat exchanger), then flows over the bananas to remove moisture and then exits the system through the exhaust fan mounted at the top of the dome.

To analyze this system, however a great number of equations are needed. Some of these equations are heat flow equations due to different heat transfer modes (such as convection and radiation), others are thermodynamic equations related to the first law of thermodynamics. The schematic below shows a cross section of the fruit drier and its different elements. It also labels different heat transfer coefficients used in the spreadsheet included in appendix D.

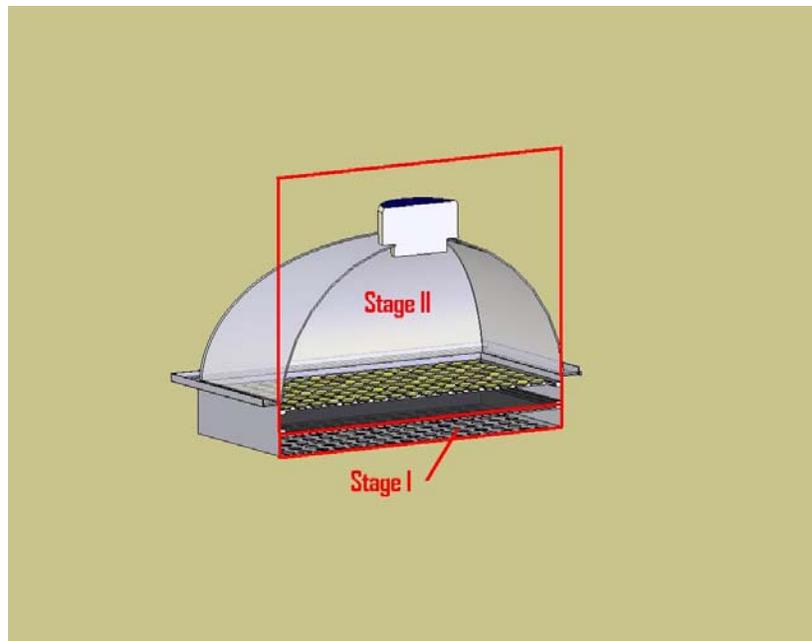


Figure 10 – Control Volumes Within Fruit Dehydrator.

The radiation heat transfer was linearized to allow for iterations to solve our system. Formula BLANK on the equation sheet represents the heat transfer coefficient h_r which is the equivalent of convection heat transfer coefficients between two radiating surfaces.

The convection coefficients were either calculated or approximated. Bananas were modeled as flat plates immersed in air flow and the mesh was modeled as cylinders perpendicular to air flow. Equations 8 and 9 in the formula sheet find the convection coefficients for these two components, respectively. Convection at the dome and the base was assumed to be free convection and the coefficients h were approximated accordingly.

To complement the heat transfer equations, thermodynamic equations were used to link the air temperatures on the right side of the thermal circuit. These equations are derived from the first law of thermodynamics and use the perfect gas model for air. Formula 4 in the equations sheet shows the dependence of air temperatures (T_7 - T_{12}) on the heat flow to the air (q_{13} - q_{18}).

To complete the number of equations needed to solve the system the incoming heat flows to different stages had to be approximated. Since all these components lie vertically an area ratio of each component in a horizontal plane was calculated and it was assumed that ratio is also the ratio of radiation absorbed by that component. The total heat flux is known so it was possible to approximate incoming energy at each level (q_1 - q_5) and this last step finally produced enough equations to solve the large matrix located in appendix D.

The next step once the temperature difference was known is to calculate the relative humidity drop. It is assumed that humidity ratio stays constant as air is heated right up until the air hits the bananas. The spreadsheet in the appendix calculates the new relative humidity for the new corresponding temperature. Next it is assumed the air becomes saturated (relative humidity is 100%) and the water transfer rate out of bananas can be calculated. Since this water transfer rate corresponds to 100% relative humidity, it is the maximum water rate out of bananas and can't be exceeded.

Another point of interest is the method with which the rate of water diffusion out of bananas was approximated. A lumped capacitance method is used to estimate the

maximum transfer rate of water into the flow. A check is important to make sure this rate of water into the flow is less than the water transfer rate corresponding to 100% relative humidity above. In other words, the goal is to make sure that the maximum water vapor transfer rate does not bring the airflow above its saturation point before exiting the system. The lumped capacitance method also helps predict the time needed to reach final state of dehydration of the bananas, thus helping to optimize the drying process for different critical lengths, (ratio of the volume to the surface area). At this point actual moisture is removed from the bananas and transported out of the system in the flow.

Once the analysis was completed the solid works model was downloaded into a software based program, Cool-It, an air flow and temperature gradient program. This program allows the designer to input solid works models and a fan volumetric flow rate (CFM) in order to determine the temperature ranges within a working system. After designing the drier, a test run of Cool-It software determined that our theoretical design temperatures would be met and maintained.

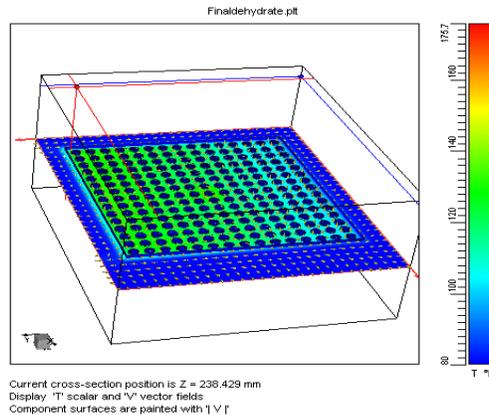


Figure 11 – Cool-It Software Tests.

Conclusion

The final design has passed rigorous tests in our simulated environment while taking into account the following design considerations:

- Cost effectiveness with no additional costs (parts, preparation, material)
- Size, weight, and ease of handling
- Quick drying time and increased product turnover (77% reduction in drying time vs. standard outdoor drying)
- ease of use
- No electricity is needed due to lack of availability in the target area

The final testing has yielded many different dried fruits in a time ranging from 6-10 hours. Pineapples were dried in a time of just over 9.5 hours the longer drying time was due to the higher moisture content of the fruit. Bananas were dried in a time of 6.5 hours and 7.5 hours. The variability of the drying time for the two different batches was a result of the ripeness of the fruit. The 6.5 hour batch was done using fully ripened bananas while the 7.5 hour batch was completed with an un-ripened crop. Mango's were also dried and found to take a little over 8 hours to dry. This time was also due to the higher moisture content in the fruit. Through the testing of different fruits it has been determined that there is great variability in drying different types of fruits and even further depends on the ripeness of the fruit. The drying times are inline with the benchmark times it takes to dry with the electric dehydrator purchased.

Our prototype cost roughly \$331 while our final mass production cost is on the order of \$48.12. The mass production cost was determined for 10,000 units through estimated

vendor mass production quotes (dome top) and estimates based on purchasing products through manufacturers rather than third and sometimes fourth parties.

Prototype vs. Mass Production Costs

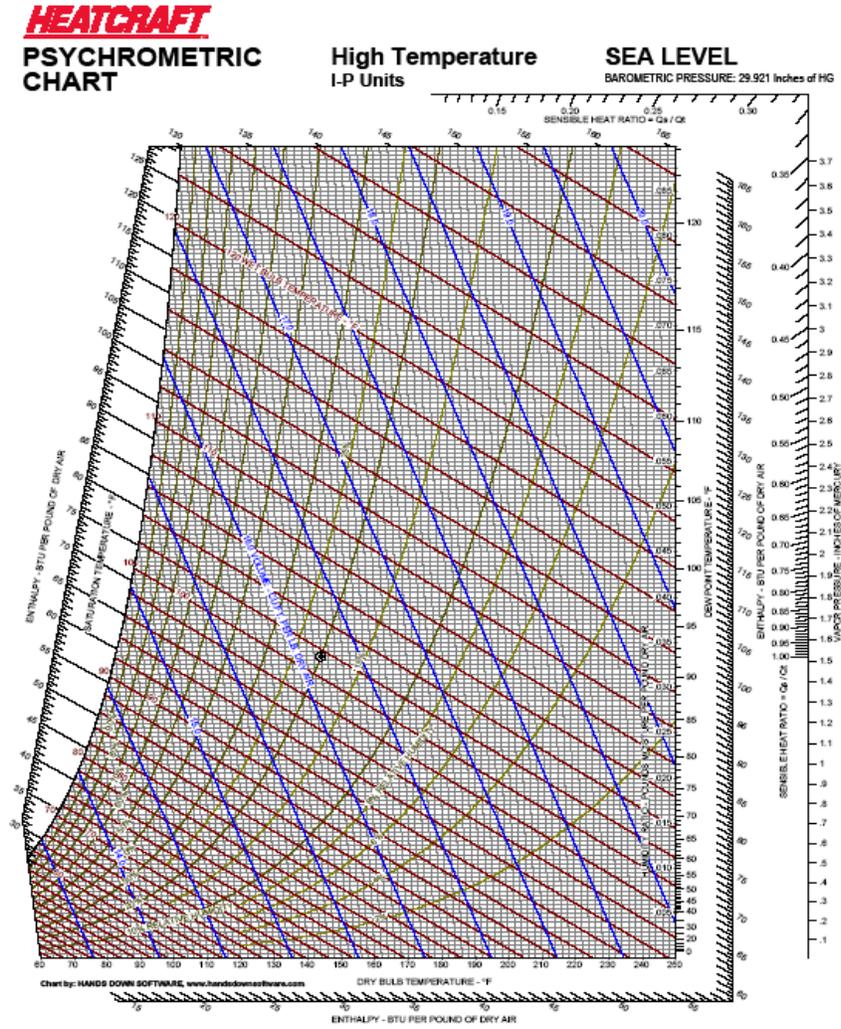
Part	Prototype Cost	Mass Prod. Cost	Reasoning
Acrylic Dome	\$90.30	\$9.12	Mass Production (10,000 Units) Est. Quote from Vendor
Solar Fan	\$66.00	\$6.50	Less Third Party Mark-up, Buy Direct from factory
Aluminum Base	\$175.00	\$32.50	Approx. 20% of Prototype (10,000 units)
Total Cost	\$331.30	\$48.12	

After finalizing our design we have identified some recommended improvements and further areas of exploration. The use of thermally-insulating coatings will reduce the heat loss to the surroundings of the base. This will also lead to using different base materials which could prove to be more efficient and cost effective. The use of legs with wheels instead of stationary feet would help mobility but could increase cost. Added height and handle location could make unit more mobile and easier to locate.

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Appendix A:



Appendix B: Stage I Mass Flow Spreadsheet

Appendix C: Stage II Mass Flow Spreadsheet

T ₁ (R)	T ₂	T ₂ (F)	T ₃	m _a	c _p	w ₁	h _{v1}	S	m _{liq}	h _{liq}	w ₂	h _{v2}	cfm
545	550	90	620	3.09	0.24	0.0257	1100.7	331	0.5	58.07	0.1429	1130.1	0.69
545	560	100	620	3.98	0.24	0.05	1105	331	0.5	68.04	0.1429	1130.1	0.88
545	580	120	620	5.55	0.24	0.0757	1113.5	331	0.5	87.99	0.1429	1130.1	1.23
545	600	140	620	23.5	0.24	0.125	1121.9	331	0.5	107.95	0.1429	1130.1	5.21
545	601	141	620	25.2	0.24	0.1261	1122.4	331	0.5	109.2	0.1429	1130.1	5.59
545	602	142	620	25.9	0.24	0.1267	1122.7	331	0.5	109.83	0.1429	1130.1	5.75
545	603	143	620	28	0.24	0.1278	1123.2	331	0.5	111.075	0.1429	1130.1	6.21
545	604	144	620	28.9	0.24	0.1283	1123.5	331	0.5	111.7	0.1429	1130.1	6.41
545	605	145	620	31.4	0.24	0.1295	1124	331	0.5	112.95	0.1429	1130.1	6.99
545	606	146	620	34.5	0.24	0.1306	1124.5	331	0.5	114.2	0.1429	1130.1	7.67
545	607	147	620	35.9	0.24	0.1311	1124.8	331	0.5	114.825	0.1429	1130.1	7.98
545	608	148	620	38.6	0.24	0.132	1125.2	331	0.5	115.763	0.1429	1130.1	8.59
545	609	149	620	41.8	0.24	0.1328	1125.6	331	0.5	115.763	0.1429	1130.1	9.28
545	610	150	620	47.4	0.24	0.1339	1126.1	331	0.5	117.95	0.1429	1130.1	10.5

Appendix D: Thermal Analysis Spreadsheet

Appendix E: Simulated Environment Cut-sheets

Appendix F: NASA and ASHRAE Data Sheets

Appendix G: Equation Sheet

$$\dot{m}_{a1} = \dot{m}_{a2} \quad (\text{dry air})$$

$$m_w = m_{v1} - m_{v2}$$

$$0 = \dot{Q}_{cv} - \dot{W}_{cv}^0 + (\dot{m}_a h_{a1} + \dot{m}_v h_{v1}) - (\dot{m}_a h_{a2} + \dot{m}_v h_{v2})$$

$$h(T_2) - h(T_1) = c_p(T_2 - T_1)$$

$$q'' = h(T_s - T_\infty)$$

$$q_{\text{rad}} = h_r A (T_s - T_{\text{sur}})$$

$$h_r \equiv \varepsilon \sigma (T_s + T_{\text{sur}})(T_s^2 + T_{\text{sur}}^2)$$

$$\overline{Nu}_x \equiv \frac{\bar{h}_x x}{k} = 0.664 Re_x^{1/2} Pr^{1/3} \quad Pr \geq 0.6$$

$$\overline{Nu}_D = 0.3 + \frac{0.62 Re_D^{1/2} Pr^{1/3}}{[1 + (0.4/Pr)^{2/3}]^{1/4}} \left[1 + \left(\frac{Re_D}{282,000} \right)^{5/8} \right]^{4/5}$$

$$\omega = \frac{m_v}{m_a}$$

$$\phi = \left(\frac{p_v}{p_g} \right)_{T,p}$$

$$\omega = 0.622 \frac{p_v}{p - p_v}$$

$$\frac{C(t) - \omega}{C_i - \omega} = \exp \left[- \left(\frac{1}{\tau_t} \right) t \right]$$

Appendix H: Cool-It Software Tests