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Solar Drying Shed for Cassava in Malawi

Design 3 BREE 495

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3 Executive Summary

Solar-shed drying of crops is a widely used technique to add value to agricultural products, as well as decrease post-harvest losses. The end product is usually stable enough to be stored for several months, free from debris and dust, and generally of higher quality than products of conventional solar drying. Considering the importance of cassava as a staple crop in developing countries, optimizing the drying process for it while minimizing energy inputs and costs is of primary importance. Therefore, the community of Chisemphere, Malawi, decided to look into alternative designs to its current solar dryer to improve the quality of the dried cassava.

In order to optimize the design process, we conducted a thorough literature review to determine the properties of cassava, as well as adequate drying structure types for this specific product in tropical conditions. In addition, we conducted lab experiments to determine the moisture content and drying kinetics of cassava, using standard methods. Considering all the constraints put on the design, including the amount of cassava to be dried, time of drying, climatic conditions, financial resources, and more, we came up with a final design of a mixed-mode natural convection solar dryer that meets most of our initial requirements. The structure was dimensioned using the design procedure outlined by Forson et al. (2007). The final structure is presented schematically in this report, along with details pertaining to the design process followed during this past semester. Further information relative to the context of this design can be found in our Design 2 proposal paper.

We hope that our design can inform the implementation of solar drying structures in the communities of Malawi, and as well as inform future projects on solar drying in the department of Bioresource Engineering.

4 Literature Review

4.1 Introduction to Cassava

4.1.1 Characteristics of Cassava

Cassava is a widely used crop for food production in developing countries, as it has numerous desirable agronomic properties including growing well in arid regions and in low-fertility soils (Angelov, Sun et al. 1993). Originally from Latin America, there are now 9.30 million hectares of cassava being cultivated in Africa alone, representing 46.28% of the annual world production (Opara 1999). In Malawi, cassava represents a staple food crop for approximately 35% of the population (Sandifolo 2003), which is indicative of its socio-economic importance in that country. Between 1994 and 2001 cassava production in Malawi has more than tripled, while yield per unit area has increased by approximately 50% (Sandifolo 2003).

Postharvest losses are generally high for cassava, since it is extremely perishable after being harvested (Opara 1999). There are high in-field crop losses due to pest, but post-harvest losses for the 2000-01 growing season were also as high as 30% for cassava in Malawi (Sandifolo 2003). Cassava roots, which are the parts of the plants that are generally consumed, usually mature in 9-24 months, depending on the cultivar and generally have a 50%-70% moisture content (Opara 1999). The latter causes the tuber to be very susceptible to deterioration. In order to reduce degradation of the product due to physical reactions and microbial growth, it is essential that the water activity of the product be reduced. Water activity (a_w) is the ratio of the vapour pressure of a particular solution to the vapour pressure of pure water at the same temperature. This parameter is also used as an indicator of how conducive a given media or food is for microbial growth, with lower a_w levels inhibiting microbial growth (Christian 2000). A water activity of 0.70, which corresponds to a moisture content of 15% in cassava, is considered as acceptable for preserving cassava and can be achieved by drying the product (Bokanga n.d.).

4.1.2 Cyanogenic Compounds in Cassava

Using cassava for human consumption poses a number of challenges, one being the removal of cyanogenic glycosides, which are present at high levels in the tuber and can be toxic for humans. This toxicity to humans is due to compounds in the cassava being degraded in the digestive system into cyanohydric acid after consumption (Monroy-Rivera, Angulo et al. 1996). The cyanogenic glycosides are composed of linamarin (95%), and lotaustralin (5%), and the former can be degraded into acetone cyanohydrins if the cassava tissue is damaged. Acetone cyanohydrins, when put in conditions similar to that of the human body (pH above 4, temperature above 30°C), can almost spontaneously degrade to cyanide (Montagnac, Davis et al. 2009). Currently, different methods are being investigated to detoxify cassava, with sun drying being the most common method used in the transformation sector. Sun drying is considered a desirable method because it does not have significant infrastructure needs or costs (Monroy-Rivera, Lebert et al. 1991). Sun drying, independent of other processing methods used, results in significant decreases in the amount of cyanide present in cassava, as can be seen in Table 1 below.

Table 1: Effects of drying processes on cyanogens content of cassava roots.

Processing methods	Cyanide retention %	Total HCN mg HCN/kg
Oven-drying[a]		
Fresh root	100	140
50 °C, 10-mm chips	46.4	65
50 °C, 3-mm chips	64.2	89.5
70 °C, 10-mm chips	60	84.5
70 °C, 3-mm chips	74.2	104
Sun-drying[a]		
Fresh root	100	140
10-mm chips	27.8	39
3-mm chips	53.1	75
Crushing and sun-drying[a]		
Fresh root	100	165
	2.1	3.5
Sun-drying by time[b]		
Fresh root	100	1090
8 d sun-drying	54.2	591
17 d sun-drying	36.8	401
Repeated pounding + sun-drying[b]		
Fresh root	100	513
	14.6	75

Enzymes are also present in the mitochondria of cassava cells that can successfully degrade cyanogenic glycosides, themselves present in the cell vacuoles, to prevent the formation of cyanide. In order for this degradation to occur, the cassava cell mitochondria have to be severed to release these enzymes and enough water has to be present in the product to allow the enzymes to interact with the cyanogenic compounds present (Monroy-Rivera, Lebert et al. 1991). Therefore, it has been suggested that the drying process of cassava should begin at night, rather than in the morning, to allow for these compounds in the cut cassava to interact before the drying process really begins (Monroy-Rivera, Angulo et al. 1996). In fact, the cassava is simply allowed to sit prior to the actual drying. Furthermore, studies indicate that lower drying temperatures decrease the cyanogens retention in the cassava roots (Monroy-Rivera, Lebert et al. 1991; Montagnac, Davis et al. 2009). Overall, the effects of different processing methods on cyanide retention in cassava roots are summarized in Table 1 above.

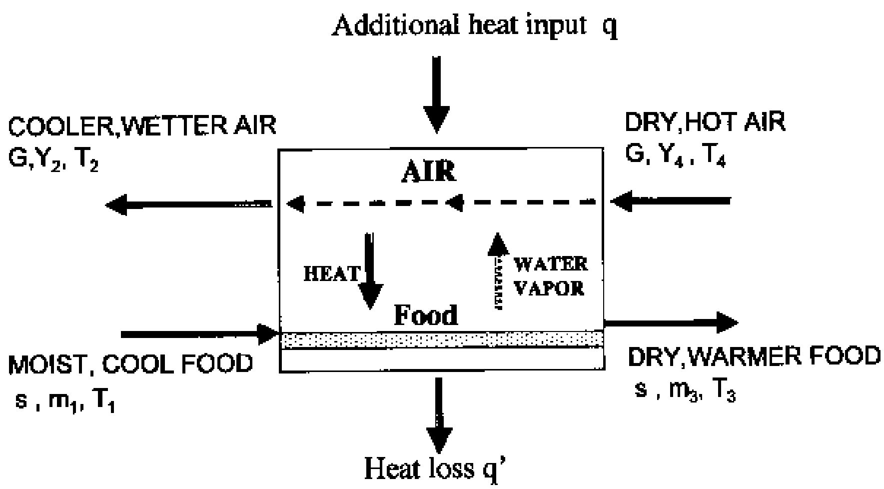
4.2 Physical Mechanisms Involved in Drying

4.2.1 Basic Principles

Drying of food materials is in principle a fairly simple process: the food is placed in a medium such as air where the partial pressure of water is low and is kept in that environment until the food's water content drops to a desirable level. However, the physical processes involved in drying, including heat and mass transfer processes, are highly difficult to model and predict, partially due to the complexity and heterogeneity of biological materials. Heat transfer processes are essential to drying in that they provide the energy necessary to transform the liquid water present in the food material into vapour form. Mass transfer processes affect the ability of water in liquid or vapour to move through the food material and enter the air at its surface (Karel and Lund 2003).

While modeling these phenomenon within a particular food material can be challenging, Karel and Lund (2003) created an excellent schematic shown in Figure 1 that displays the overall energy and mass balances (based on a unit of time) of a drying system that utilizes air as the drying medium.

Figure 1: Schematic representation of material flows in a dryer.



Where

s= mass of food solids entering and leaving the dryer in the unit time [kg]
G= mass of dry air entering and leaving the dryer in the unit time [kg]
m=moisture content [kg water/ kg food solid]
Y=relative humidity [kg water/kg dry air]
q=additional heat [kJ], which in the case of our design would be solar heat
q'=heat loss [kJ]

The mass balance of such a dryer system is given by Equation 1:

$sm_1 + GY_4 = sm_3 + GY_2$ [1]

The energy balance of the system is given by Equation 2:

$q + G\{c_{pA}(T_2 - T_4) + c_{pV}Y_2(T_2 - T_4)\} = q' + s(m_1 - m_3)[c_{pV}(T_4 - T_3) + \Delta H_V] + sc_{ps}(T_3 - T_1) + sm_1(c_{pL})(T_3 - T_1)$ [2]

Where
c_{pA} is the specific heat of air (kJ kg^{-1} $^oC^{-1}$)
c_{pV} is the specific heat of water vapour (kJ kg^{-1} $^oC^{-1}$)
c_{ps} is the specific heat of solids (kJ kg^{-1} $^oC^{-1}$)
c_{pL} is the specific heat of liquid water (kJ kg^{-1} $^oC^{-1}$)
ΔH_V is the latent heat of vaporization (kJ kg^{-1})

The above energy balance assumes that vaporization takes place at the food exit temperature, T_3, and that the latent heat of vaporization of the water being removed from the food is the same as the latent heat of water (Karel and Lund 2003). Now that we have overviewed the overall energy and mass balances of the dryer system we can focus more specifically on the mechanism of water movement through a food material in the paragraphs below.

4.2.2 Mechanisms of Water Movement

As will be discussed below, during the initial stage of drying the water lost from a food material being dried is largely the water on the surface of the product. Once that water has been evaporated, water must move through the material to the surface in order for drying to continue. This movement of water during the drying of food product is the result of three forms of water transport including the diffusion of liquid water, capillary transport and finally the diffusion of vapour water, which dominates the later stages of drying processes. As outlined by Karel and Lund (2003) differences in water concentration in various parts of the food material, and more specifically the interior of the material versus the surface from where water is evaporating, drive the diffusion of liquid water through the material. The rate of this diffusion is given by Equation 3:

$$\frac{dw}{dt} = -DA\frac{dc}{dx} = -DA\rho_s\frac{dm}{dx} \qquad [3]$$

Where
D is the diffusivity of liquid water in the food (m^2/s)
dw/dt is the diffusional flux of water (kg/s)
A is the cross sectional area of diffusion
C is the concentration of liquid water (kg/m^3)
ρ_s is the density of solids (kg/m^3)
m is the water content (kg water/kg solids)
x is the distance in direction of diffusion

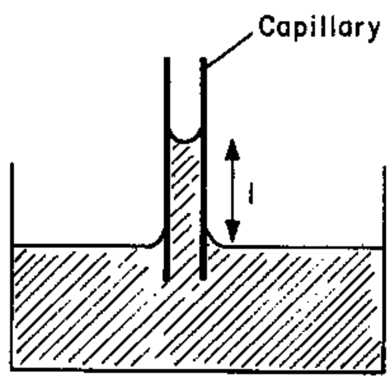
Since biological materials are also typically composed of a series of small interconnected pores, capillary action also plays a role in water transport. The movement of water in such capillaries depends on their radius. The height to which capillary action will pull water in a given capillary is shown in Figure 2 (Karel and Lund 2003) and defined by Equation 4:

$$l = \frac{2\gamma}{rg\rho_L} \qquad [4]$$

Where

l is the pressure difference as height of water [m] (i.e. How high a given capillary can pull water)
r is the capillary radius [m]
g is acceleration due to gravity [m/s^2]
ρ_L is the density of the liquid [kg/m^3]
γ is the surface free energy

Figure 2: Schematic representation of capillary rise.



Source: Karel and Lund (2003)

Because of the complexity of the systems of capillary tubes that exist within a food material it is common to express the movement of liquid water within a food substance during drying as an overall liquid diffusivity, D_L, that includes liquid water diffusion and capillary flow (Karel and Lund 2003). As a result, the overall rate of liquid water movement is found using Equation 5:

$$\frac{dw}{dt} = -D_L A \frac{dc}{dx} = -D_L A \rho_s \frac{dm}{dx} \qquad [5]$$

When less water remains in the food product near the end of the drying process, the remaining water typically moves through the material via water vapour diffusion, which is governed by Equation 6:

$$\frac{dw}{dt} = -Ab\frac{dp}{dx} \qquad [6]$$

Where

b is the permeability of the material [kg m^{-1} Pa^{-1} s^{-1}]
p is the partial pressure of water [Pa]

4.2.3 Drying Rates

At the beginning stages of drying a wet food product, such as cassava, the removal of water from the product is essentially the same as the evaporation of water from the surface of a water body. This phase of drying, which occurs after a very brief period at the very beginning of drying during which the water on the food surface is warming up, is called the “constant rate” phase of drying. During this phase water is removed from the surface at a steady rate of mass of water per m^2 of exposed surface. Major factors affecting the rate of evaporation during these beginning stages include the temperature, humidity, pressure and velocity of the air as well as the temperature of the water in the food product. The direction of movement of air relative to the food surface and the size and shape of that surface also effect this initial drying rate (VanArsdel 1973).

After a period of “constant rate” drying, the rate of evaporation of water from the material will begin to decrease as the water being removed from the material becomes less accessible. This second stage of drying is referred to as the “falling-rate” phase of drying and will continue until all of the water within the material (that is not hydrostatically bound) has been removed (VanArsdel 1973).

4.3 Solar Drying Structures

4.3.1 Structure Comparisons

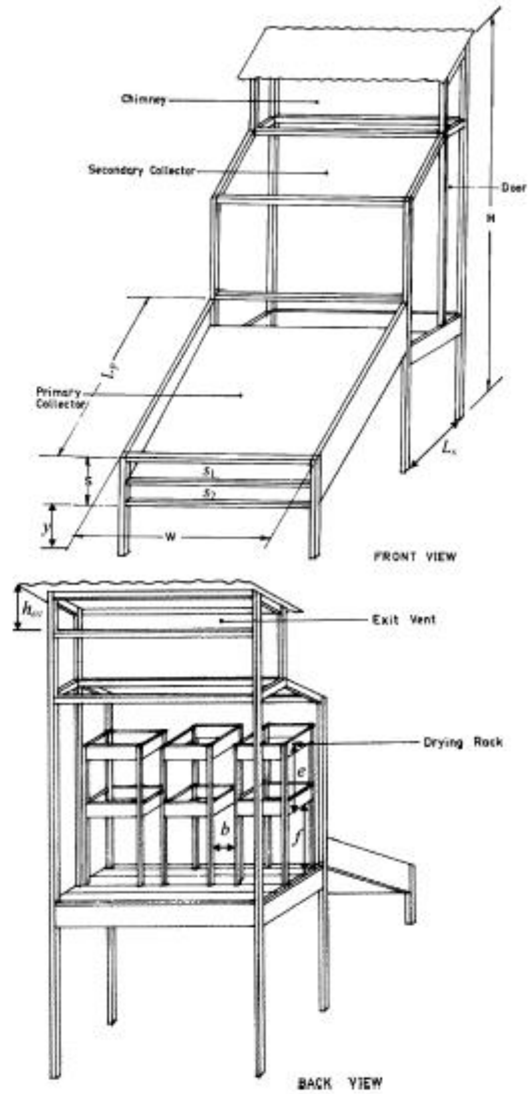
Solar drying is a common practice in developing countries, particularly open-air solar drying, but this causes high weather dependence and vulnerability to product contamination by debris and product damage by pests (Forson, Nazha et al. 2007). Various types of solar dryers for drying agricultural products have been designed to address these concerns. While some systems with forced convection requiring higher energy inputs have been studied (Bala and Woods 1995), the focus of this project is on potential solar dryer structures that require no electrical inputs and rely on natural convection, caused by temperature gradients, to execute the air process. Natural convection solar dryer design can be classified into three different categories; indirect-mode dryers, direct mode dryers and mixed-mode dryers. Indirect-mode dryers are typically composed of a compartment or room of dark, opaque walls that prevent solar radiation from reaching the material being dried. Air entering these dryers air is preheated in a separate structure before entering the drying chamber. In contrast, the air entering direct-mode dryers is not preheated and the walls of the structure are transparent, so solar radiation heats the product directly. Finally, mixed-mode dryers have both transparent walls and an air preheating device (Afriyie, Nazha et al. 2008). Considering the previous characteristics, the following criteria should be used when choosing a drying structure for developing countries (Chua and Chou 2003):

1. Low initial capital costs;
2. easy to construct and fabricate with available natural materials;
3. easy-to-operate with no complicated electronic/mechanical protocol;
4. effective in promoting better drying kinetics and product quality than the sun-drying method;
5. easy to maintain all parts and components; and
6. simple replacement of parts during breakdowns.

Different structures offer various efficiencies, depending on the meteorological characteristics of the region where the solar dryer is to be located, as well as the nature of the agricultural product being dried (Forson, Nazha et al. 2007). The main purposes of drying structures are to protect the crop from pests and contamination by debris, to increase the drying temperature, and to reduce the relative humidity of air passing through the structure to improve drying conditions. It was shown that for cassava at 70% moisture content, in ambient air conditions of 80% RH and 32°C, the presence of a solar drying structure can increase the temperature up to 45°C and reduce the relative humidity down to 40%, increasing up to eight times the dehydration potential of ambient air (Ayensu 1997). However, this specific dryer was constructed from glass sheets, and extremely well insulated with different materials such as polystyrene, which might not be available or feasible for a project in Malawi.

Also, although no electricity is available through a network in the region where the drying shed will be installed, the use of a diesel generator to operate a fan and a heater could be an option (Chua and Chou 2003). This could allow producing a higher quality product, through a faster and more efficient drying process. However, due to large travel distances and poor transportation infrastructure, and energy being too expensive for poor farmers, most believe this is not a viable alternative (Ekechukwu and Norton 1999). Therefore, the most appropriate system would be a low temperature, passive (natural convection) solar-energy drying structure. After comparison between different structures, the mixed-mode natural convection solar crop-dryer was determined to be the most efficient dryer for tropical humid climates (Forson, Nazha et al. 2007). This structure is schematically described in Figure 3:

Figure 3: Schematic Views of the Mixed-Mode Natural Convection Solar Crop Dryer



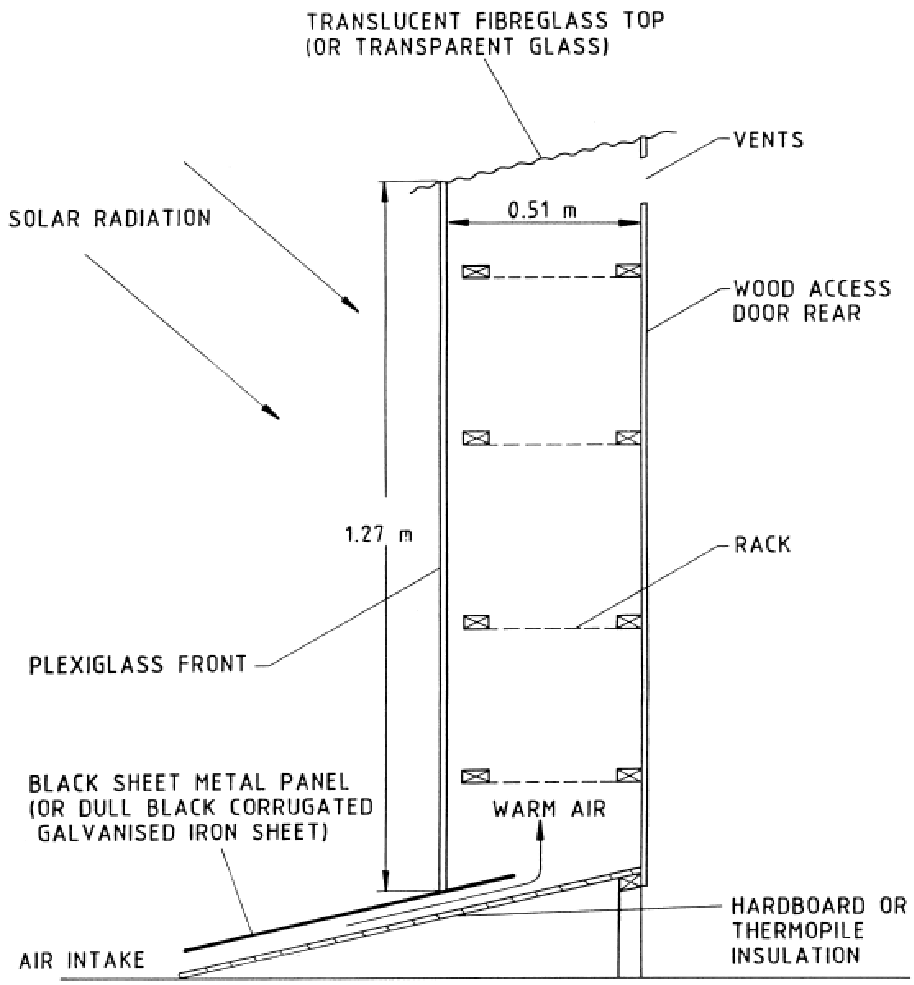
Source: (Forson, Nazha et al. 2007)

The shape of the structure has an important influence on the air flow rates present inside it. In fact, some studies indicated that a roof more inclined towards the vertical plane would also have increased air flow rates, explaining why tent dryers (having an inclined roof) are preferred to cabinet dryers, independent of the weather conditions (Afriyie, Nazha et al. 2008). However, they also noted that an increase in air flow rate can only increase the drying rate under a certain relative humidity, in the case of cassava this limiting relative humidity is 60%. Therefore, in a region such as Malawi where the drying is done during the rainy season and where relative humidity levels are constantly above 60%, increasing the air flow rates through the drying structure would have minimal effects on drying rates.

One question raised during the design proposal process was whether or not using a continuous process for drying cassava, in which cassava at multiple moisture contents present in the dryer at one time, would have an influence on the drying rate. No such considerations were ever noted in literature, but reports of a simple design of the mixed-mode solar dryer to allow the drying of different materials simultaneously were found (Ekechukwu and Norton 1999). More specifically, a multi-stacked design was reported by Lawand at the Brace Research Institute, Canada, to dry different crops simultaneously shown in Figure 4, and was descirbed follows (Ekechukwu and Norton 1999):

> The dryer consists of a bare-plate air-heating solar-energy collector (made from a black painted metal panel) or corrugated galvanized iron sheet (painted dull black) with either hardboard or thermopile insulation and a multi-stacked drying chamber glazed on the front side and at the top. The air exit is via rear side vents, thus the dryer is not equipped with a chimney. However, the tall column of the drying chamber (about 1.27 m) was expected to generate the necessary buoyant head for the natural convective air flow. Loading and unloading of the dryer is accomplished via a wooden access door at the rear. The glazed front is oriented appropriately, depending on the location of the dryer.

Figure 4: Lawand Multi-Stacked Design for Solar Crop Drying



Source: Ekechukwu and Norton (1999)

Drying of several moisture contents simultaneously can be found analogous to the simultaneous drying of different materials, so this design suggests that drying multiple moistures contents simultaneously could be feasible.

4.4 Peripheral Structures

There are three main types of peripheral structural additions that can be incorporated into a solar dryer design to decrease the amount of time required to dry a product. These include solar chimneys, solar collectors and solar energy storage devices.

4.4.1 Solar Collectors

Solar collectors, also commonly called solar air-heaters, intake ambient air at one end and this air passes out of the other end of the collector into the main drying chamber. The purpose of solar collectors is to preheat the air before it enters the drying chamber, thereby increasing the amount of water that can be taken up by a given volume of air (Rozis and Guinebault 1995).

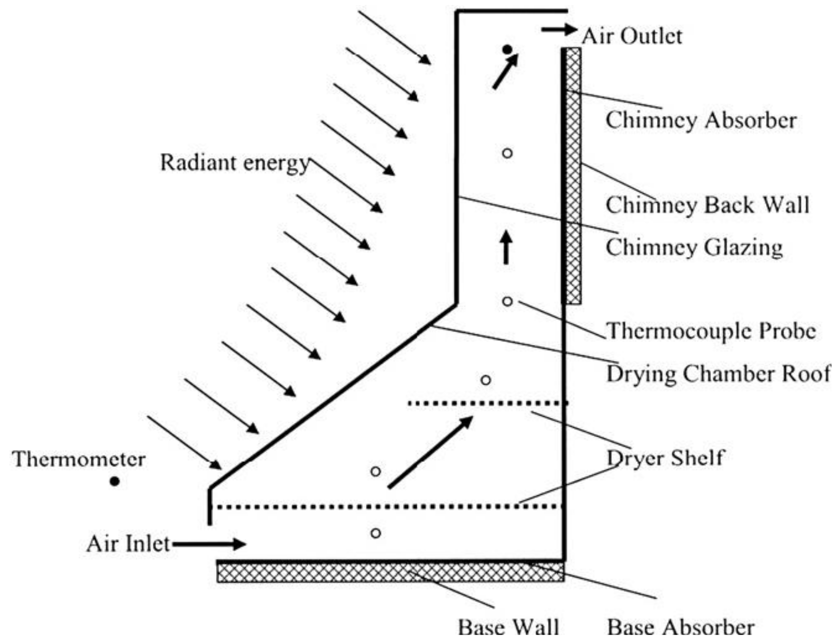
These devices are typically long surfaces covered with a transparent material composing the top and a dark colored material forming the bottom of the collector with air passing between both sides by natural convection. The transparent material should ideally insolate the hot air inside the collector from the ambient air to minimize heat losses and it should be durable and resistant to damages due to excessive heat (Rozis and Guinebault 1995). While glass is typically considered the ideal material, a plastic sheeting material would more likely be used in the context of this project due to its lower cost and wide availability. Insulating material, such as polystyrene, cardboard material, dry sand or straw, is also commonly placed on our under the bottom of the solar collector to minimize heat losses to the exterior thereby maximizing the heat transfer to the air flowing through the collector (Rozis and Guinebault 1995; Santos, Queiroz et al. 2005).

There are multiple possible configurations for solar collectors however the most effective configuration for solar drying systems relying on natural convection to drive air movement was determined by multiple authors including Ong (1982), Close (1963) and Macedo and Altemani (1978) to be the single pass double duct solar air heater (SPDDSAH), an example of which can be seen in Figure 3 above. Some authors suggest that the incorporation of solar collectors may be impractical for systems in rural communities in developing countries due to their large size and, as a result, relatively high (Afriyie, Nazha et al. 2008). However, it should be noted that under some circumstances solar collectors make drying possible under environmental conditions that would otherwise be prohibitive and that cause drying durations that would result in substantial amounts of post-harvest losses.

4.4.2 Solar Chimneys

The basic principle of the solar chimney is similar to that of the solar collector; a solar chimney aims to heat air. It consists of a dark surface that is exposed to solar radiation and is also in contact with the air to be heated. The chimney intakes air from the main drying chamber and by heating it further, decreases its density causing rise and exit the chimney thereby motivating air flow out of the solar drying chamber (Das and Kumar 1989). The chimney increases the buoyancy force, which is dependent on the density of air outside the structure and within the chimney, and promotes higher airflows in solar dryers (Afriyie, Nazha et al. 2008). One example of a solar chimney can be seen in Figure 3 above and another possible model is shown in Figure 5 below.

Figure 5: Solar Chimney

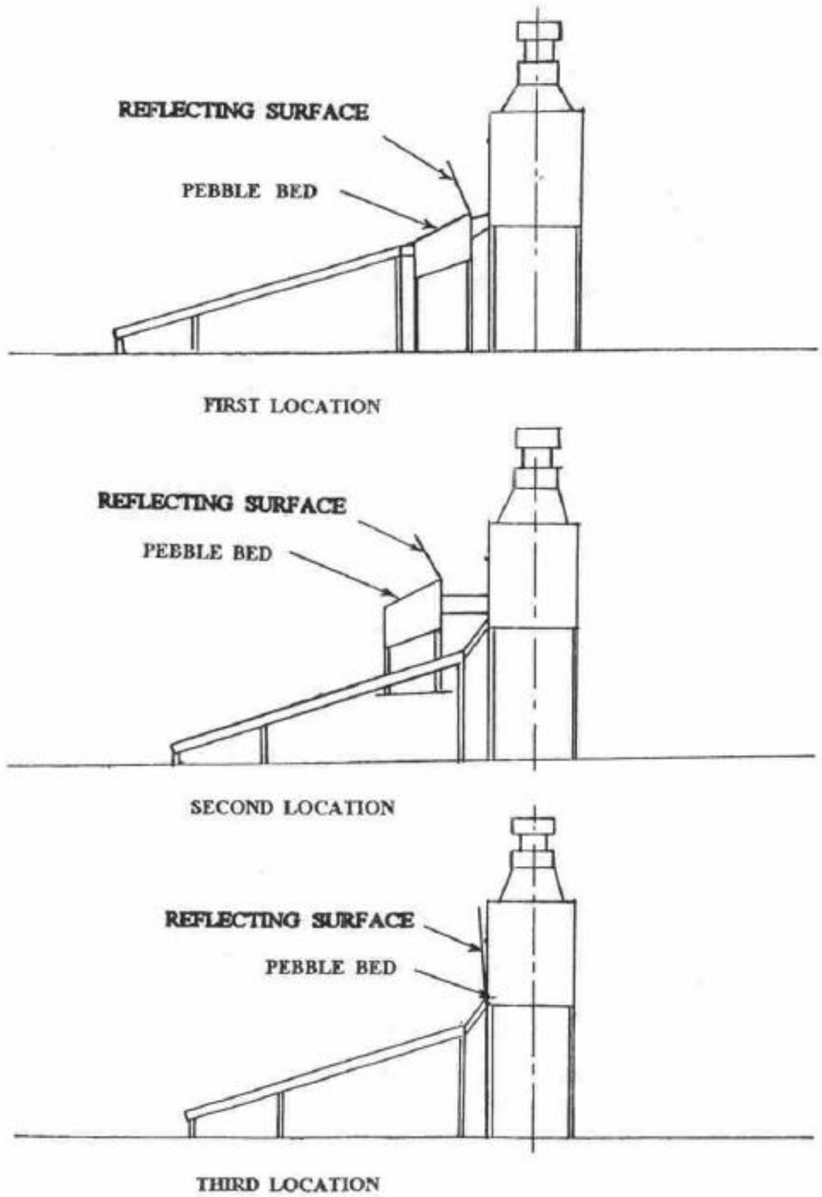


Source: Afriyie, Nazha et al. (2008)

4.4.3 Solar Energy Storage

Khattab and Badawy (1996) explain that one of the greatest challenges to achieving reliable food drying in a minimal amount of time using solar drying is that solar energy is a fairly low density energy source and is not consistently available at the same intensity over the drying periods. In particular, the temperature inside a solar dryer tends to decrease at night, when there is no incoming solar radiation. This results in a decrease in the rate at which water is being removed from the product and could result in some of the water vapor in the air condensing back onto the product. In order to minimize these effects it has been suggested that mechanisms to store solar energy be incorporated into a structural design to increase the average temperature inside the structure when there is no incoming solar radiation. Rock or pebble beds are one effective method of storing solar energy that is relatively simple to implement and inexpensive (Khattab and Badawy 1996). Khattab and Badawy (1996) investigated three possible positions for such a pebble bed, as seen in Figure 6 below, and evaluated the effect of each on the temperatures within the drying chamber over 24 hours.

Figure 6: Pebble Bed Positions



Source: Khattab and Badawy (1996)

Positioning the pebble bed in the second location yielded the highest increase in temperatures over the 24 hour period, followed by the first location and finally the third location.

5 Laboratory Experiments and Procedures

5.1 Description of the Experiment Design Process

One crucial design step identified in our proposal was to determine the drying behavior of cassava, commonly referred to in the literature as a product's drying kinetics, when it is dried under various temperature conditions and in layers of different thicknesses. In order to establish these characteristics we contacted Graham Lettner to ascertain how to best reproduce the size reduction methods utilized at the cassava drying facility in Chisemphere. It was determined that the most accurate way to reproduce the 'pulped' cassava that is produced on site in Malawi using a simple grinder of sorts, would be to use a cheese grater with fine holes. As a result we decided to use a food processor with a fine grating attachment to prepare cassava for our experiments.

It should be noted that we chose to conduct our experiments inside a drying oven which is significantly different from the conditions experienced by drying cassava in Malawi. Firstly, there is forced air movement within the oven while air moves by natural convection in a solar dryer. Secondly, the relative humidity of air inside the solar drier is significantly lower than the humid conditions that exist in Malawi, particularly during the rainy season. Thirdly, the temperature inside the oven was relatively constant while in reality the drying cassava would experience fluctuating temperatures. Also, the properties of the cassava being dried in Malawi, including initial and final moisture content, bulk density as well as the temperatures experienced by the cassava inside the drying shed are unknown due to a lack of equipment for accurately performing such measurements. The exact thickness of cassava layers being dried in the current shed is also unknown, though Graham Lettner advised us that the layers were typically uneven in depth and the photos we had access to displayed an approximate maximum thickness of 3cm. In spite of all of this, Yvan Gariepy, a researcher in the Bioresource Engineering Department, advised us that conducting a drying experiment in the ovens available would at least provide us with a starting point for our design and illustrate magnitude of the differences in drying behavior of cassava when it is dried in layers of different thicknesses and at different temperatures. Due to the multiple unknowns concerning the characteristics of cassava at the time that we were establishing our experimental procedure Yvan Gariepy advised us that 60°C would likely be a good temperature to use in our experiment because such conditions typically dry food material effectively while avoiding damaging the material due to excessive heat. As a result we chose 50, 60 and 70 degrees as our test temperatures. Lastly, because the current cassava layers that are being dried appear to have a maximum thickness of 3cm we chose 1, 2 and 3cm as our test thicknesses to determine the effect of layer thickness on required drying time.

5.2 Material and Methods

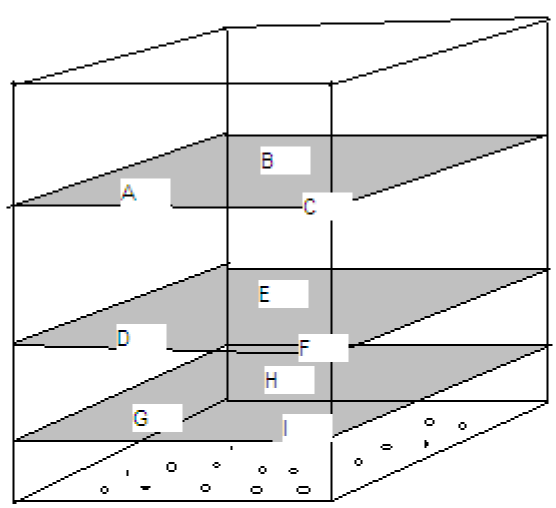
5.2.1 Establishing the Initial Moisture Content

The initial moisture content of the cassava was first established using a normalized method consisting in drying a sample of approximately 20g of grated cassava for 48 hours, at 105°C in a conventional oven (PRECISION, Thermo Electron Corporation, USA). The cassava was peeled by hand, and then grated using a kitchen food processor (BRAUN), which in turn produced chips with the following average dimensions: 1mm thick, 2mm wide, and 24mm long. Three samples were prepared, being placed in aluminum plates and weighed prior to dying. The three samples of cassava were placed in the oven, one sample on each shelf, left to dry for 48h. After that period, the samples were weighed again, and the moisture content was established. An average value of the moisture contents of the three samples was used in the subsequent calculations of drying kinetics.

5.2.2 Establishing the Drying Kinetics of Cassava

This section of the lab experiments used same procedure for peeling and grating the cassava as was used in the portion of the experiments that established the initial moisture content of cassava. Three aluminum plates were filled with cassava for each of the three different thicknesses tested (1cm, 2cm, and 3cm) resulting in nine plates in total. These were then weighed and placed in the oven at 60°C. The samples were placed randomly in the oven, with one sample of each thickness on each shelf, for a total of three samples per shelf. Then, the samples were weighed at pre-established times as follows: 5 minutes, 15 minutes, 25 minutes, 45 minutes, 60 minutes, 2 hours, 4 hours, 8 hours, 16 hours, 32 hours, and 48 hours. The same procedure and configuration was then used for two more temperatures: 50°C and 70°C. Figure 7 is a schematic representation of the experimental setup:

Figure 7: Experimental Setup in Conventional Oven



5.3 Results

5.3.1 Initial Moisture Content

The data obtained using the first methodology to determine the moisture content of the cassava is presented in Table 2 below. The initial mass is presented as the wet mass, where the dry mass is the final mass of the samples after 48h in the oven.

Table 2: Determining the Moisture Content of Cassava

Sample Number	Wet mass of cassava(g)	Dry mass (g)
1	21.03	8.40
2	19.86	7.86
3	20.30	7.82

From this data, it was possible to establish the moisture content of the cassava, using Equation 7:

Total Moisture content % = 100*[(Wet Mass – Dry Mass)/ Wet Mass]   [7]

Table 3: Experimental Results of Moisture Content

Sample Number	Moisture Content %
1	60.05706134
2	60.42296073
3	61.47783251

Therefore, taking the mean of these values, we find the initial moisture content to be 60.7%. This value was used for the drying at 50°C and 60°C, since the drying at 70°C yielded results where the final moisture content was below 0%, indicating that the value of 60.7% was too low for these samples. As mentioned earlier, normal values for moisture content in cassava vary from 50% to 70%, this value being well within the acceptable range. In addition, these drying values were used as ideal comparisons rather than pure replication of natural conditions, where temperatures would be lower. The final moisture content at 70°C was therefore calculated by assuming that after 48h the cassava was entirely dry.

5.3.2 Drying Kinetics of Cassava

The moisture content of the cassava was established at different times during the drying process, for all three thicknesses and three temperatures, therefore providing an indication of how much time it would take, given these variables (thickness and temperature), to dry cassava to the desired moisture content of 15% on a wet basis. The Equation 8 used to establish the moisture content at any time t is the following:

$$\text{Moisture content \% at time t} = [m_0 * MC_0 - (m_0 - m_t)] / m_t \qquad [8]$$

m_0: Initial mass of the sample
MC_0: Total moisture content
m_t: Mass of the sample at time t

Graphs displaying the results of these experiments can be found in Appendix 1.

Colour changes were also observed during the drying process; more specifically darker colours appeared in the 3cm layer samples, regardless of the temperature used. The lighter colours, which represent the higher value cassava, were generally present in the 1cm layers, probably because their surfaces dried at a higher rate than the other samples.

5.3.3 Discussion of the Results

An important point to note is that there were some issues concerning the reliability of the oven for maintaining a constant temperature; when conducting the experiment at 50°C, the temperature raised to 80°C between 120 minutes and 240 minutes, rendering the results inaccurate for that particular batch. However, the temperature at all other moments for all three batches remained fairly constant.

The 9 graphs in Appendix 1 clearly show that the three replicates for each thickness exhibit similar drying kinetic behaviours. However, the samples located on the bottom shelf on the oven (Samples G, H, and I), tended to dry faster, as they were closer to the circular air vents present at the bottom of the oven. However, we can be fairly confident that the following results comparing the effect of the different temperatures on drying times are representative.

The time required to reach 15% moisture content can be roughly interpolated from the graphs in Appendix 1 and the results of this interpolation are presented in Table 4 below.

Table 4: Time required at different temperatures and thicknesses to reach a wet basis moisture content of 15% in cassava chips

	Thickness		
Temperature	*1 cm*	*2 cm*	*3 cm*
50°C	900 minutes	1400 minutes	2500 minutes
60°C	525 minutes	1000 minutes	2150 minutes
70 °C	450 minutes	750 minutes	1250 minutes

The results presented in Table 4 indicate that there is approximately a doubling of the time required to dry cassava between 70°C and 50°C, regardless of the thickness of the layer of cassava. Furthermore, the time required to dry a 1cm layer is about half of the time required to dry a 2cm layer, and one third of the time required to dry a 3cm layer, and this independently of the temperature used to dry the cassava. The conclusion is therefore evident; thinner layers, at higher temperatures, will dry much faster than thicker layers, at cold temperatures. However, there is no need to go to temperatures as high as 70°C, considering that there is only a 25% difference between that temperature and 60°C. In the context of a solar drier, it may be more difficult to raise the temperature by an extra 10°C than simply using a longer period of time to dry the cassava.

6 Final Design

6.1 Conclusions of Literature Review and Experiments

From the literature review it is clear that all three types of peripheral devices for solar dryers described would be advantageous to add to our design. However, there is little available in the literature indicating how to appropriately design a solar energy storage device, and such a device was is not included in the design procedure and calculations by Forson, Nazha et al. (2007), outlined below, that formed the backbone of our design. As a result, a solar energy storage device was not included in our design but a solar collector and a form of solar chimney will be included.

After conducting our experiments, we determined that the optimal thickness to dry cassava would be approximately 2cm, as it would allow the construction of a smaller structure for the same capacity than a smaller layer thickness, while preventing colour changes due to drying rates too low like what was observed for 3cm layers. In addition, because cassava starts degrading at 70°C and higher, it would not be advantageous to use such a high temperature for drying. In addition, when comparing the time differences needed to dry the cassava, large differences were observed between 50°C and 70°C, while 60°C was much more efficient than 50°C. Therefore, considering the energy necessary to reach an extra 10°C in temperature, it was decided that 60°C would be optimal, which is also what had been reported in literature. Finally, due to the nature of cassava and the presence of high levels of cyanogenic glycosides, it was determined that to remediate this the cassava would need to be processed and chipped, then left to sit for about 6-12hours (at night), and then dried.

6.2 Preliminary Design Calculations

The simplest of design calculations for solar drying structures face many challenges. As outlined by Rozis and Guinebault (1995) certain theoretical design parameters, including the efficiency of heat and mass transfer between air and the product, the efficiency of solar energy capture and resistances to air movement, are difficult to predict, essentially in the absence of a full scale model that can be tested under the environmental conditions of the project site. They also point out that different food materials have very different properties each of which could react differently in various solar dryer designs set in a wide range of environmental conditions. Furthermore, standardized design procedures indicating how to appropriately design a solar dryer do not exist. The majority of authors tend to generate a design independent of any mathematical design project and implement their design to evaluate it, instead of modeling it in advance. However, in spite of the challenges involved, Rozis and Guinebault (1995) and Forson, Nazha et al. (2007) both laid out series of calculations that aim to form the backbone of a solar dryer design. After initially performing the calculations of Rozis and Guinebault (1995), the results of which are found in Appendix 3, it became clear that the approach of these calculations were not appropriate for our project. As a result, we chose to pursue the calculation procedure outlined by Forson, Nazha et al. (2007), which yielded much more reasonable results. This series of calculations and their results are outlined in the following paragraphs.

6.2.1 Airflow Requirements

The first step in designing a solar dryer is to determine the air flow requirements of the structure in a series of steps. The average drying air temperature rise can be found using Equation 9 below which is a modified form of the empirical formulae presented by (Macedo and Altemani 1978)

$$\Delta T = 2\beta(T_b - T_c)\left(\frac{I_t}{I_o}\right) \quad [9]$$

Where

ΔT is the temperature difference between the expected mean temperature of the heated air at the collector outlet and the ambient air temperature, which is also T_o - T_a [°C]

β is the dimensionless parameter whose value ranges between 0.14 – 0.25 (Macedo and Altemani 1978)

T_b is the boiling temperature of water at atmospheric pressure [°C]

T_c is the freezing temperature of water at atmospheric pressure [°C]

I_t is the intensity of radiation incident on the plane of the collector [W/m^2]

I_o is the maximum intensity of the source radiation, also called the solar constant which has a value of 1367 W/m^2 (Forson, Nazha et al. 2007)

For this design we let $T_b - T_c = 100^oC$, I_t=448 W/m^2 which is the average solar radiation in Chisemphere, Malawi in December (Stackhouse and Whitlock 2008), and β =0.2. The resulting ΔT in the collector is 13.1^oC.

The amount of moisture to be removed from the food material being dried can be used to determine the total mass flow of air required for drying. The mass of moisture to be removed (M_W) can be found using Equation 10.

$$M_W = \frac{W_W\left[M_{i,wb} - M_{f,wb}\right]}{\left(1 - M_{f,wb}\right)} \qquad [10]$$

Where

W_W is the initial mass of the material to be dried
$M_{i,\ wb}$ is the initial moisture content on a wet basis
$M_{f,\ wb}$ is the final moisture content on a wet basis

For this design we let W_W=600kg, $M_{i,\ wb}$=0.6 and $M_{f,\ wb}$=0.15 and the resulting M_W is 317.65kg.

The volume of air (V_A) required to remove this M_W of moisture is found using Equation 11 below.

$$V_A = \frac{M_W L_t R_a T_a}{C_{pa} P_a \left(T_o - T_f\right)} \qquad [11]$$

Where

R_a is the specific gas constant [286.9 J/kg K]
P_a is the partial pressure of dry air in the atmosphere, which is given by $p_a = \rho_a R_a T_a = 1.018*10^5$ N/m^2
C_{pa} is the specific heat capacity of air at constant pressure [1006 J/kg K]
T_f is the temperature of air leaving the drying bed, which is given by $T_a + 0.25\{\Delta T\} = 25.575^oC$

T_a is the ambient temperature [22.8 ^{o}C or 295.8K]
T_o is the temperature of drying air leaving the air heater, which is given by $T_a + \Delta T$ = 35.8 ^{o}C

Also, L_t is the enthalpy of vaporization which can be found using Equation 12:

$$L_t = R_g T_c T_b \ln\left(\frac{P_c}{10^5}\right)\frac{(T_c - T_{pt})^{0.38}}{(T_c - T_b)^{1.38}} \quad [12]$$

Where

R_g is the gas constant for water vapour [461.5 J/kg K]
T_b is the boiling point of water [100^{o}C]
P_c is the critical pressure of water [2.206*10^{7} Pa]
T_{pt} is the temperature of the product [^{o}C]
T_c is the critical temperature of water [377 ^{o}C or 650K]

Since the water to be evaporated is bound water within the product it is recommended that the value be increased by a value of 10-20% (Forson, Nazha et al. 2007). Also, T_{pt} can be estimated by finding the weighted mean of the temperatures of air entering and leaving the crop drying area using the equation T_{pt} =0.25{3T_o+T_a} (Forson, Nazha et al. 2007). T_a is set to 22.8^{o}C which is the lowest average monthly temperature during the months that cassava will be dried (Stackhouse and Whitlock 2008) and T_o is 35.8^{o}C , from the results found above. As a result, T_{pt} =32.55 ^{o}C or 305.55K and subsequently L_t = 1.9398 * 10^{6} J.

Then by inserting the necessary variable defined above into Equation 11 and then increasing the result by a factor of 15%, which is the mean of the recommended range of increase that was mentioned above, the total volume of air required is found to be 49 919m^{3}.

The volume flow rate is found using Equation 13:

$$\dot{V} = \frac{V_A}{t} \quad [13]$$

Where t is the total time required to dry cassava to the desired moisture content.

In the total time of drying t is taken to be 86400s (i.e. 24hr) the volume flow rate will be 0.578m^{3}/s. This figure can be converted into mass flow by multiplying by the density of air, which is approximately 1.2kg/m^{3}. The mass flow rates for a 24hr drying period are 0.6936 kg/s and both of these mass flow rates fall within the recommended range of 0.02-0.9kg/s (Forson 1999).

6.2.2 Area of Drying Bed

In our lab experiments we determined that an appropriate drying layer thickness for cassava is 0.02m and that the bulk density of cassava to be approximately 600kg/m^3. This design must be able to accommodate 600kg of cassava at a time so the resulting surface area of drying bed required is 50m^2, which would have a loading density of 12kg/m^2. This value is within the acceptable range of loading densities of 5 – 18 kg/m^2 recommended by Forson, Nazha et al. (2007).

6.2.3 Total Area for Collecting Solar Energy

The effective total surface area required for collecting incident radiation is related to a factor called the overall system drying efficiency (η_d) by Equation 14 below.

$$\eta_d = \frac{M_W L_t}{I_t A_T t} \qquad [14]$$

Where

A_T is the total area of the dryer receiving incident radiation (i.e. the total surface area of the primary and secondary collectors)
t is the total time
L_T is the latent heat of vaporization
I_t is the intensity of radiation incident on a tilted surface
M_W is the mass of moisture to be removed

While values for overall drying efficiency for solar dryers can range widely depending on the crop being dried, the loading densities and weather conditions, a typical range of values for natural convection solar dryer is 10% to 15% (Brenndorfer, Kennedy et al. 1987) and it is considered appropriate to take the mean of that range to achieve an optimal design (Forson, Nazha et al. 2007). Based on calculations performed and data provided above, we also let M_W =317.65kg, L_t = 1.9398 * 10^6 J, I_t=448 W/m^2 and t=86400s. The resulting A_T from Equation 14 using these parameters is 127.35m^2. Forson, Nazha et al. (2007) indicate that a ratio of drying chamber area, A_{dc}, to collector surface area, A_{sa}, of 1.0 is recommended and both should have an equal value of 63.675m^2.

6.2.4 Sizing and Dimensioning the Primary Solar Collector

By taking the ratio of length, L_p, to width, W, of the solar collector to be 1.5, which falls within the ratio range recommended for optimum performance by Forson (1999) and is the ratio used by Forson, Nazha et al. (2007), we find that W=6.52m and L_p =9.77m. To facilitate ease of construction, we'll round those dimensions to W=6.5m and L_p =9.8m. The breadth of the drying chamber, B, is made to equal W and the resulting length of drying chamber to achieve the necessary A_{dc} is also 9.8m.

6.2.5 Other Dimensions of the Dryer

Equation 15 can be used to determine the air duct depth required.

$$V_c = \frac{\dot{V}}{sW} \qquad [15]$$

Where

V_c is the average velocity at the exit of the air heater [m/s]
V is the volume flow rate [m^3/s]
s is the air duct depth [m]
W is the air duct width [m]

From the data above we let W=6.5m, V= 0.578m^3/s and V_c =0.3m/s, based on an estimate by Forson, Nazha et al. (2007). The resulting air duct depth is 0.3m. This depth also meets the design constraint that 20< L/s= 32.7 <400.

To find the height of the chimney vent we combine the equation for the cross-sectional area of the chimney ($A_v = L_s \boldsymbol{h}_{cv}$) and the equation for the cross-sectional area of the solar collector duct ($A_d = sW$) with the recommended ratio of A_d over A_v equal to 2. The resulting height of the chimney, h_{cv}, is then found to be 99mm, which could be rounded to 100mm for simplicity. Lastly, the chimney width should equal W.

6.2.6 Pressure Drop Over the Drying Bed and Height of Hot Air Column

One of the final steps in the design procedure recommended by Forson et al. (2007) involves determining the pressure drop over the drying bed. The results of that calculation are then to be used to determine the minimum height of the exit vents above the primary collector inlet that will allow moist air to escape to the atmosphere by natural convection, commonly called the height of the hot air column. We also performed these calculations and the results can be found in Appendix 4. However, upon consulting with Dr. Raghavan, it was determined that despite their use by Forson et al. (2007), such calculations are inappropriate for a design such as ours where the air is not being forced through the food material being dried. Therefore, we did not use the results of these calculations in our design.

6.3 Other Structure Considerations and Characteristics

The dimensions of our final solar dryer design are primarily based on the calculations shown above but a number of other decisions pertaining to the structures form needed to be made during the design process.

6.3.1 Interior Arrangement

As was mentioned above, the surface area of shelving required was determined based on the expected amount of cassava that is required to be dried by the structure per week, which is 600kg. Using the optimal drying bed thickness determined in our lab experiment of 0.02m it is clear that 50m^2 of surface area is required to accommodate the cassava to be dried inside the structure. We decided to have two units of shelving with sufficient space on both sides of each unit to allow people to have sufficient access to the surfaces , which subsequently allowed the widths of the units to be slightly larger than they would have been in the units were only accessible from one side. After calculating numerous possible widths and lengths of the shelving unit, it was decided that the width of the shelves should be 1.5m and, to allow for a pathway to exist near the door of the structure, the maximum length of the shelves was set to 8.3m. As a result, two layers of shelves for each shelving unit were required to provide sufficient surface area. The spacing between each of the shelves in each shelving unit was based on the recommendations of a solar drying unit designed by the Brace Institute (Ekechukwu and Norton 1999) and was set to 30cm. Also, to allow for sufficient space for people to work and place the cassava on the top shelf, it was determined that space of a minimum height of 0.5m should exist above the top shelf of each unit. Lastly, the height of the bottom shelf of each unit was made sufficiently high so that it would be above the outlet of the solar collector into the main drying chamber.

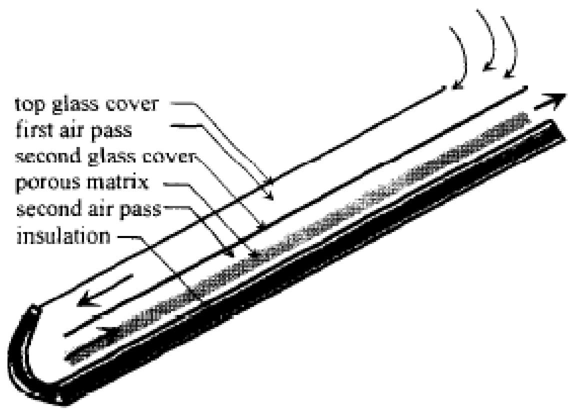
6.3.2 Solar Capture Surface Slopes

The slopes of the roof and solar collector needed to be established during the design process. While the literature indicates that such slopes should be equal to the latitude of the location of the structure (Duffie and Beckman 2006) in our case this was unfeasible. The latitude of Chisemphere, Malawi is approximately 12 degrees south of the equator. Due to the large surface areas required to capture sufficient heat to dry cassava in our situation, if we were to apply this 12 degree angle to our solar capture surfaces, the height of the structure would have been over 6m in height, which would likely be difficult and expensive to construct. As a result, we instead based the angles of those surfaces on ensuring that they had a sufficient slope to prevent water from pooling on the surfaces and on recommendations from Dr. Samson Sotocinal, in the Department of Bioresource Engineering. From this, we determined that the slope of our solar energy collection surfaces should be 2 degrees. While this appears to be far from the 12 degrees recommended in the literature, we feel it would be sufficiently effective given that the site location is relatively close to the equator. Also, it should be noted that the structure should be oriented so that its large solar collection surfaces face north, because the structure is located in the southern hemisphere.

6.3.3 Solar Collector Details

Double pass solar collectors, like the one shown in Figure 8, have been shown to result in higher increases in air temperature compared with single pass solar collectors (Wijeysundera, Ah et al. 1982; Mohamad 1997). However, they are impractical for our design because it is not a forced air system and instead relies on natural convection.

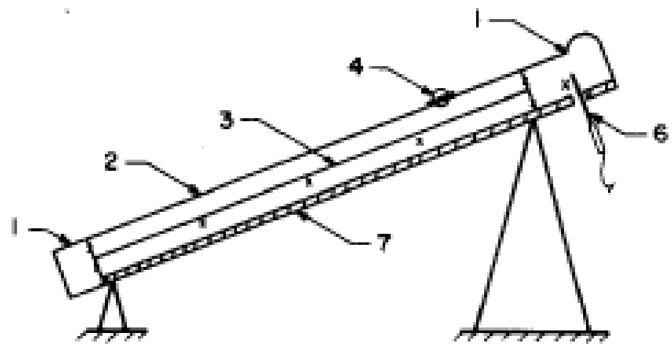
Figure 8: Example of Double Pass Solar Collector



Source: (Mohamad 1997)

Macedo and Altemani (1978) tested a number of different single pass solar collector designs and found that the most effective design had a glass cover and contained two channels of air flow separated by a metal panel, which had been painted black, as shown in Figure 9 below. The collector also had a layer of insulation on its bottom surface to minimize heat loss to the environment. This is the solar collector style that we chose to implement in our design, except our design will not incorporation the measuring devices Macedo and Altemani (2007) included in their experiment.

Figure 9: Solar collector setup: 1-Wind protection, 2- Glass cover, 3- Metallic absorber, 4- Radiometer, 6- Thermoanemometer, 7-Styrofoam insulation



Source: (Macedo and Altemani 1978)

Forson, Nazha et al. (2003) showed in their research that the ratio of the height of the top air channel in the solar collector to that of the bottom channel can impact the temperature increase in the air passing through the collector. They determined that a ratio of 1.1 to 3.5 results in optimum performance, so for the purpose of our design we chose a ratio of 2, which is the same ratio used by Forson, Nazha et al (2003).

For insulating solar collectors, Rozis and Guinebault (1995) recommend 5-15cm of polystyrene insulation, which should be placed on the bottom of the collectors to prevent heat losses. They also indicate that in terms of insulating ability 18cm of dry sand and 6cm of dry paper or carton material can be considered as being approximately equivalent to 3cm of polystyrene (Rozis and Guinebault 1995). For our design we initially wanted to use polystyrene as an

6.3.4 Structural Analysis

There are two primary types of loads that will be experienced by the members of our structure; wind loads and dead loads. For the purposes of this project we attempted to perform a preliminary structural analysis taking into account these two types of loads in order to determine the spacing of supporting members or studs along the structure's exterior walls. However, we are far from being trained as structural engineers and a comprehensive structural analysis of our solar dryer design is largely outside the scope of our program and this project. Also, the material properties of the wood being utilized in construction in Malawi and the appropriate design factors for structural design for that region are unknown making it challenging to proceed with standard Canadian structural design practices. As a result, our attempt at estimating the loads that the structure would need to withstand are outlined below but further and more comprehensive structural design calculations were not feasible and are not included in this document. A complete analysis of the structure would need to be performed by qualified persons if this project were to be constructed in reality.

6.3.4.1 Structural Loads

Snow loads

Snow loads are typically significant in the design of Canadian structures but there is no significant snowfall in Malawi at any time of year, so snow loads are not considered in this context.

Dead loads

As outlined in subsection 4.1.4. of the National Building Code of Canada (NBCC), the dead load must include:

- the weight of the member itself
- the weight of all materials of construction incorporated into the building to be supported permanently by the member
- the weight of partitions
- the weight of permanent equipment
- forces due to prestressing

The weight of the plastic covering of our material can be considered negligible for our structure, so the only material contributing to the dead load on the members in the wall of the structure would be the weight of any members in the roof of the structure. This weight would be equal to the cross sectional area of the member, multiplied by the member, multiplied by the density of the wood being used, multiplied by standard gravity and finally multiplied by the number of members in the roof.

Wind Loads

The wind load on a structures surfaces can be found using the following equation (Canadian Wood Council 2005):

$W=I_w q C_e C_g C_p$

Where

I_w=importance factor for wind velocity
q = reference velocity pressure
C_e= exposure factor
C_g= gust effect factor
C_p = external pressure coefficient

In Canada, wind velocity pressures typically experienced by structures at various geographical locations can be found in the Canadian National Building Code. However, a wind velocity pressure (that also encompasses exposure, importance and gust factors), called q' in these calculations, can also be calculated for other locations by using the following equation from the Midwest Plan Service (1987):

$q'=0.00256 \times V^2 \times K_zG \times I^2$

Where

q'= effective velocity pressure, psf
V= wind velocity at 33’ elevation for a 50-yr recurrence interval, m/s
K_zG= combined building height, location exposure and gust factor
I^2= importance factor

Because our structure is less than 15ft in height and is in a fairly exposed location, K_zG=1.07. Also, the importance factor for the building can be taken to be 1.0, because the structure being designed is an agricultural building that requires reasonable reliability to protect property and people (Midwest Plan Service 1987).

The wind velocity at 33’ elevation for a 50-yr recurrence interval for Chisemphere, Malawi is unknown but it is known that the average annual wind velocity at 10m elevation over the past 10 years is 3.75m/s, while the wind speed at an elevation of 50m above the ground at this location does not generally rise above 10m/s (Stackhouse and Whitlock 2008) . As a result, we will take 10m/s as a conservative estimate of the wind velocity at 33’ elevation for a 50-yr recurrence interval in this area.

$q'= 0.00256 \times V^2 \times K_zG \times I^2$
$q'= 0.00256 \times (10m/s)^2 \times 1.07 \times 1.0$
q'= 0.27392 psf or 0.0131kPa

The modified wind load for this structure would be:

$W=q'C_p$

Unfortunately, the C_p factor is not typically determined independently of C_g and because gusting was already taken into account in the K_zG factor in the calculation of q', we cannot use the C_gC_p factors typically used for determining wind loads in Canadian structures (Canadian Wood Council 2005). As a result, we are unable to accurately and effectively determine the wind load on our structure.

6.3.5 Termite Control

In our initial design report we had indicated that we would attempt to address the threat that termites pose to the existing solar drying structure. In reviewing the list of materials used in the construction of the current structure it became clear that a chemical compound called chlordane was used in the original structure to prevent termite damage. Chlordane is a pesticide that is not found naturally in the environment and was originally intended for use on crops including citrus fruits and corn as well in landscaping applications. The Environmental Protection Agency in the United States banned all uses of the chemical except for the control of termites in 1983 and they decided to ban all uses in 1988. Chlordane is very persistent in the environment and can have negative effects on the nervous system, digestive system and liver of people exposed to the chemical by breathing air near structures treated for termites or who ingest foodstuffs contaminated with chlordane(Agency for Toxic Substances and Disease Registry (ATSDR) 1994). Due to these potential environmental and health effect, we would like to recommend that chlordane not be used in the construction of a drying structure in the future. Some chemical methods that are currently being used as alternatives to chlordane and other organochlorine chemicals include phenyl-pyrazoles, organophosphates, carbamates and synthetic pyrethroids, all of which can be applied to foundation and soil surrounding a structure to protect against subterranean termites. Other chemical preservatives such as creosote and copper or more commonly available substances like engine oil or kerosene can also be applied to wood directly to protect against termites. These chemicals may also have negative health and ecosystem impacts but are considered less detrimental than chlordane.

Unfortunately, there are few other feasible options available for termite control (Langewald, Mitchell et al. 2003). Using a termite resistant material such as steel instead of wood is largely impractical in the context of our project due to the high cost of such materials. Termite mounds can also be physically destroyed to control termites populations but this method is fairly time and labour intensive (Langewald, Mitchell et al. 2003). Fungi and microbial based methods of biological control have shown some promise (Langewald, Mitchell et al. 2003) but their applicability in the context of Chisemphere would depend on access to the appropriate strains of microorganisms and facilities in which they could be propagated, which is likely unfeasible.

6.3.6 Runoff and Erosion Management

When constructing a new structure, like our proposed solar drying structure, it is important to consider the multiple potential impacts of water on the design. Drawing from consultation with Dr. Robert Bonnell in the Department of Bioresource Engineering and our knowledge from previous courses in the Department concerning these issues, we have generated a series of considerations that apply to managing water for structures such as these. Firstly, due to the large surface areas of our structure, it is essential that some means be incorporated to deal with runoff coming from the structure's roof and solar collector surface. One simple way to do this would be to install a gutter of some sort along the northern edge of the roof that would direct the runoff into either a ditch alongside the building or a storage tank or underground cistern of some sort. A storage tank could be advantageous for our design because, although most drying will be occurring when rain is plentiful in Malawi, the region of Chisemphere can receive as little as 3mm of precipitation per month during its annual dry season, during which time the stored water would be highly valuable. Based on average monthly rainfall data pertaining to Chisemphere, Malawi as estimated by a NASA program (Stackhouse and Whitlock 2008), the surfaces of the structure would intercept approximately 63 m^3 of water annually and the storage tanks would need to be sized appropriately.

Secondly, it is important to consider the position of the structure in its surrounding watershed and topography. Ideally the structure would be located in a slightly elevated area to prevent water runoff from eroding away the soil around the structures base slab during rain events. However, if the positioning of the structure's site is such that it experiences substantial water-flow, then channels of ditches could be dug to divert the water from passing over the soil underneath the structures.

6.3.7 Miscellaneous

Other design features that are important to note are that the structures should be oriented on the site so that its solar energy collection surfaces face north. Also, the material chosen to form the base of each of the shelves is a screen material to allow more air to flow over the surface of the cassava to accelerate drying. However, the strength of material of screen in Malawi is unknown and so either that data would need to be found or tests would need to be performed to see if the material could withstand the cassava loads before implementing this design. Lastly our current design has a concrete slab as its base which is similar to the base of the existing structure, but is made completely of concrete as opposed to having a dirt floor in the centre.

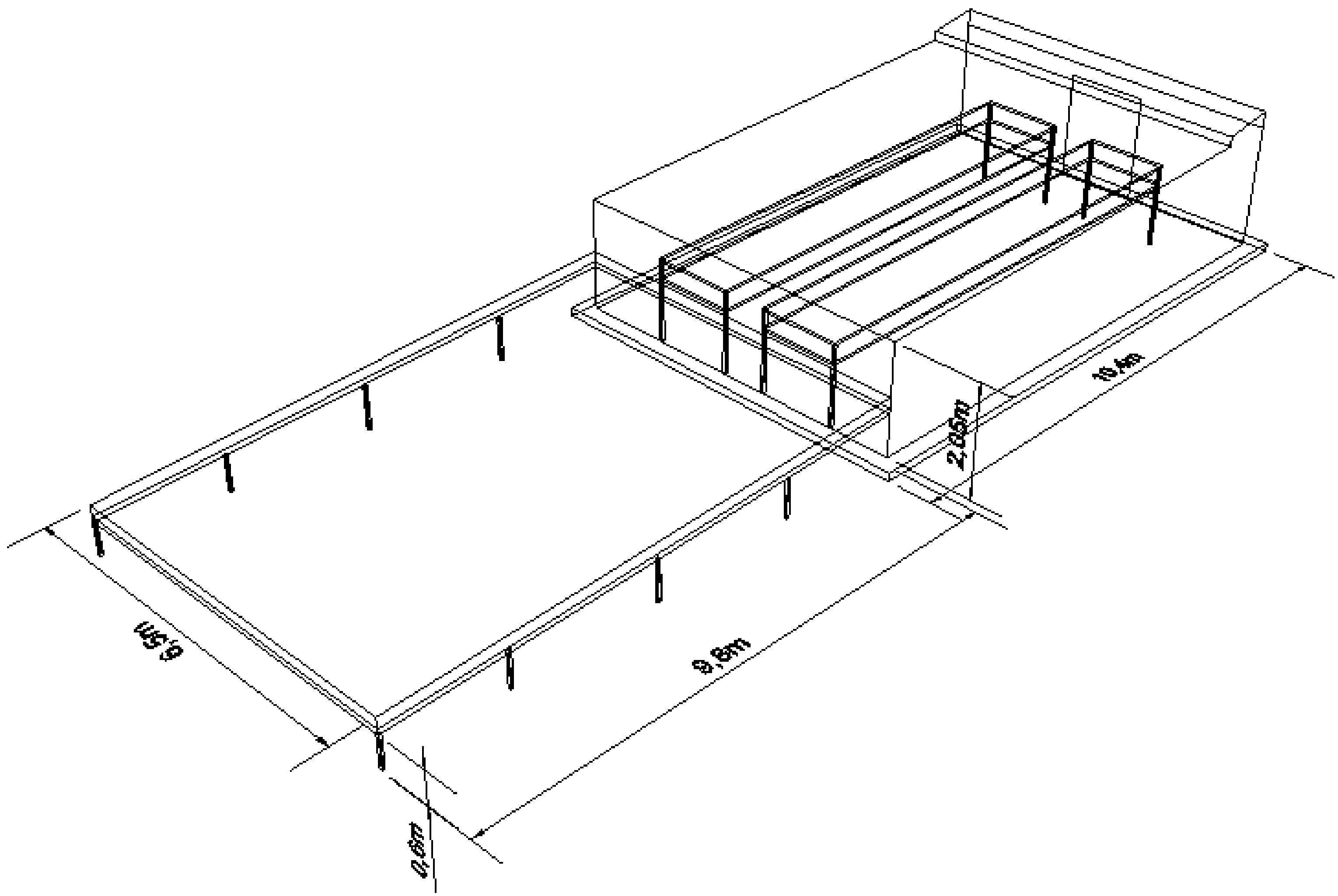
It should also be noted that Forson, Nazha et al. (2007) advise that the minimum inlet height for the solar collector should be 0.4m with a height of 0.6m being considered preferable.

6.4 Other Recommendations Improve Drying Efficiency

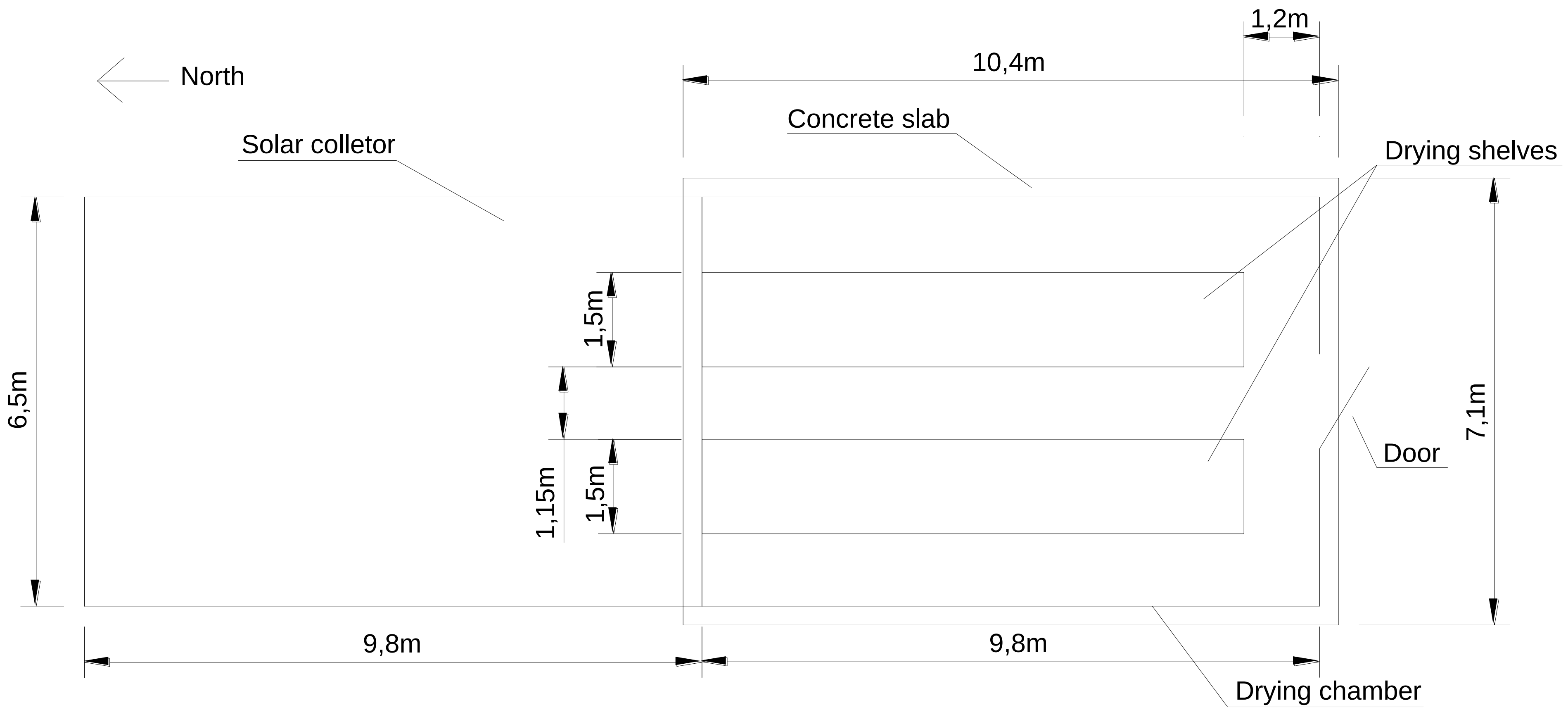
There are numerous techniques that could be used to reduce the moisture content of cassava before and during drying in order to further decrease the amount of drying time required. First of all, before drying begins, a press could be used to remove as much water from the crop as possible. However, this would also cause the cyanide removal process to be compromised and further studies would have to be conducted for any precise recommendations to be made. In second place, the use of a screen rather than a uniform plastic sheet for drying in the shed could help the airflow through the product, and therefore increase the drying rate of the product. Once again, there are downsides to this alternative, as the small cassava chips could get stuck in the grid and over time block any flow of air. Alternatively, too large a grid would not be able to hold the cassava in place and would be useless in our case. A compromise, based on the size of the cassava chips, would be needed. Therefore, another challenge would be to have perfectly uniform batches of cassava chips, which might not be feasible. In last place, and probably the most adequate alternative for the solar drying of cassava, would be the introduction of a levelling device to obtain layers of cassava uniform in thickness. This would be a simple technology, at low costs, and adaptable to any change in drying conditions. A simple system could be designed, such as a U-shaped wooden device with sides as long as the required thickness of the cassava bed and top as wide as the shelf depth. In this case, sides would be approximately 2cm long to match the recommended depth of cassava in each layer.

6.5 Final Design Diagrams

6.5.1 3-D View

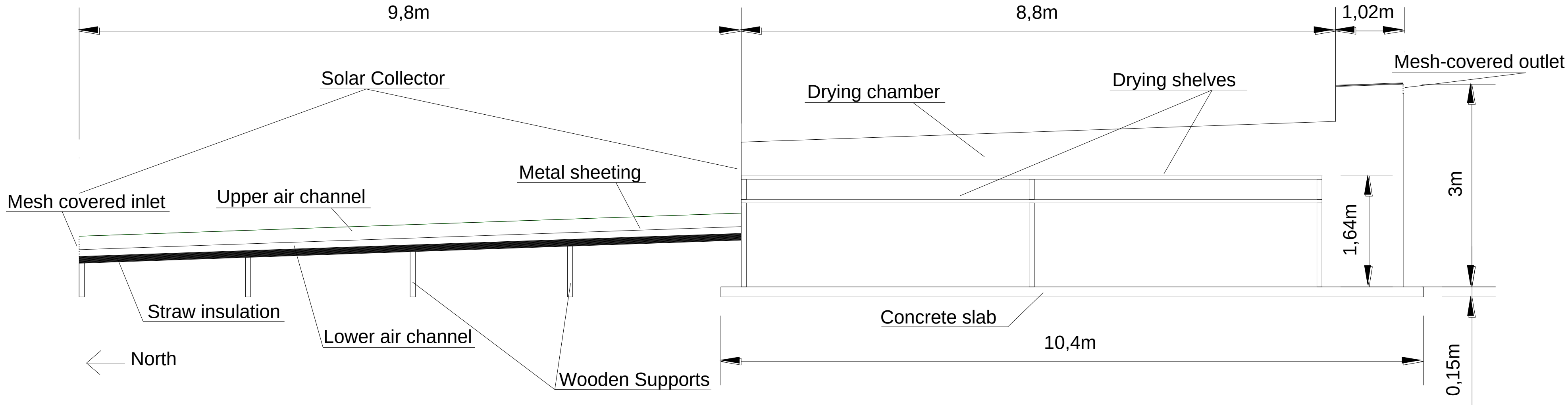


6.5.2 Top View

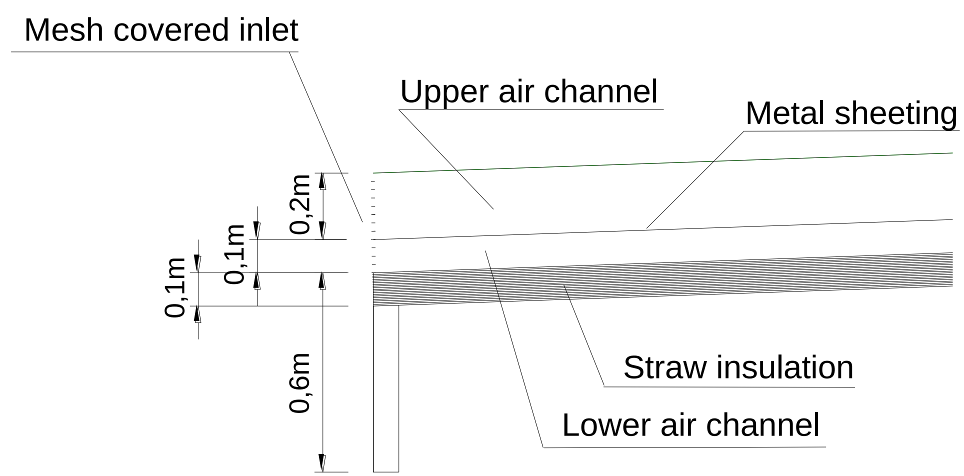


1,2m
10,4m
North
Concrete slab
Solar colletor
Drying shelves
1,5m
6,5m
Door
7,1m
1,15m
1,5m
9,8m
9,8m
Drying chamber

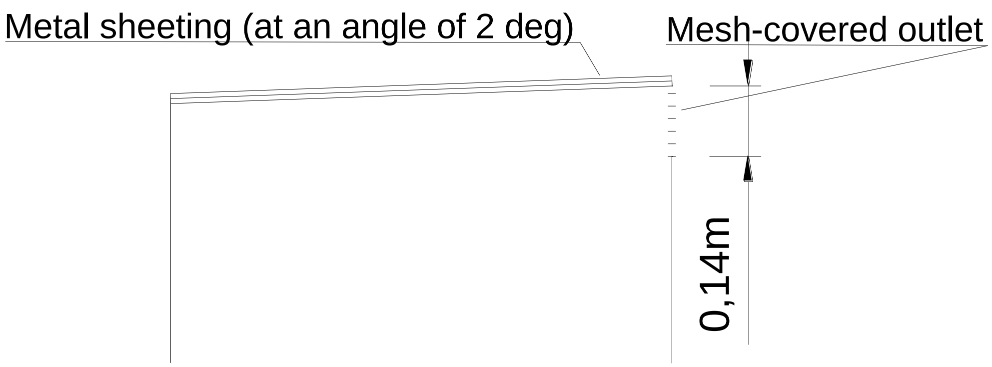
6.5.3 Side View



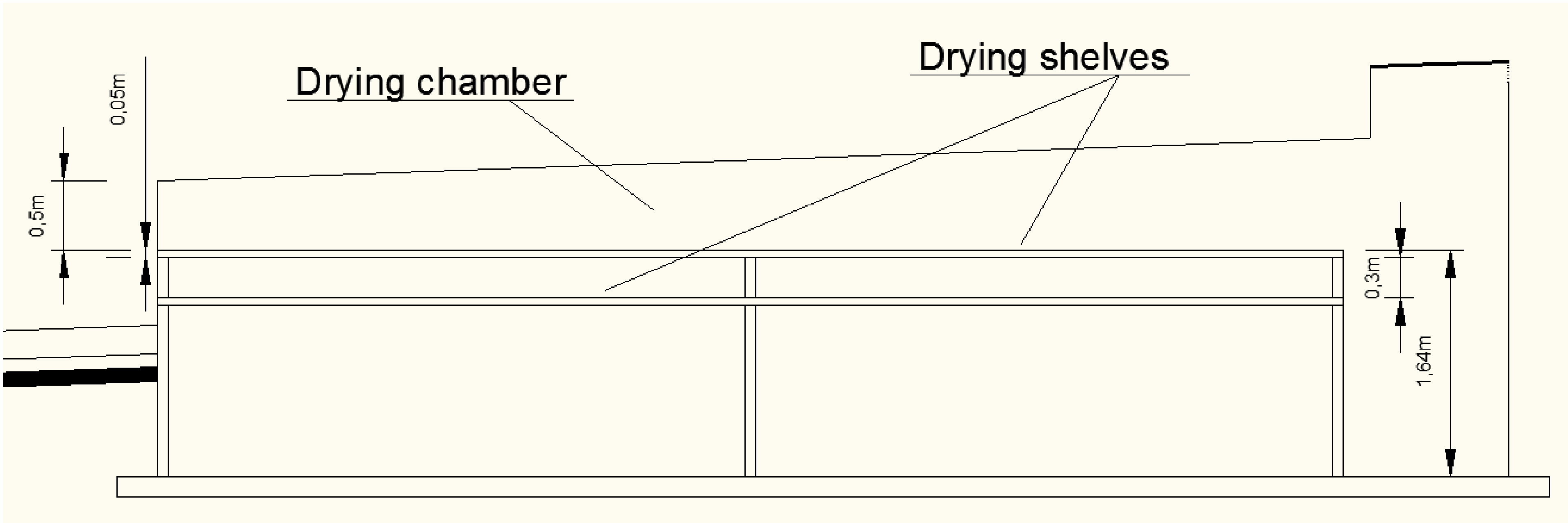
Solar Collector Inlet Details



6.5.4 Solar Collector Outlet Details



6.5.5 Drying Shelves Details



6.6 Cost Analysis and Materials

This section constitutes a short cost analysis of the structure itself. Associated costs were presented in the previous Design 2 proposal report. Materials that were not utilized in the construction of the initial structure were assumed to be purchasable in Malawi for the same price as in Canada. While this assumption may not be appropriate, we had no other means for estimating the cost of our design because prices for construction materials in Malawi are not readily available.

Table 5: Cost estimates of the new structure

ITEM	Quantity	Unit Price (Malawian Kwacha)	Total Cost (Malawian Kwacha)
Foundation Concrete	7.1mx10.4mx0.15m (11.08 m^3)	-	-
Sand (26% concrete)	2.88 m^3 (4.6 tonnes)	700	3220
Gravel (41% concrete)	4.54 m^3 (6.9 tonnes)	1500	10 365
Cement(11%concrete)	1.22 m^3 (35 bags)	2500	87 500
Aluminum Wire Mesh	30.5mx1m/roll 4 rolls	13 000	52 000
Shelves	4x1.5mx8.6m (51.6 m^2)	-	-
Air Inlet & Outlet	3.51 m^2	-	-
Solar collector	67.3 m^2		
Insulation	9.8mx6.5m	-	-
*Polystyrene**	*63.7 m^2 or 86 sheets (2 sheet thick)*	*2100*	*180600*
*Straw***	6.37 m^3, 0.541 ton	3360	1818
*Plywood**	63.7 m^2 or 23 sheets	3080	70840
Greenhouse Plastic Sheeting	2.44mx30.48m/roll 4 rolls	26 500	106 000
Solar collector	9.8mx6.5m 2x0.4mx9.8m		
Main structure	9.8mx6.5m		

	2.05mx6.5m 2.7mx6.5m 2x2.4mx6.5m		
Timber	-	-	-
2"x3"	120	450	54000
2"x2"	50	250	12 500
Metal sheeting* **	25 sheets (35'x1')	7290	182 245
Solar Chimney	1mx6.5m	-	-
Solar collector	63.7 m^2	-	-
Other			
Wire nails (2")	8 Kg	300	2400
Wire nails (4")	10 kg	300	3000
Wire nails (1")	4 kg	300	1200
T and G (4")	90 No.	600	54 000
Nylon ropes (0.25")	60 m	250	15000
Organophosphate	1 litre	2 500	2 500
TOTAL			>658588

*These costs were obtained from the Home Depot website (www.homedepot.ca)

** These costs were obtained from the McMaster-Cass website (www.mcmaster.com/#steel/=1byxun)

*** These costs and bulk density of straw (85kg/m^3, 24$/ton) were obtained from the following websites: http://www.fao.org/docrep/007/j4504E/j4504e08.htm

http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/faq7514?opendocument

All other costs were estimated from the costs provided for the existing structure. For instance, considering the increase in the structure's size, the timber need for the construction was estimated to double, while remaining in the same proportions. The needs for other materials such as nails were also estimated to double.

Also, as was mentioned above, we did not perform a complete structural analysis of our design because the material properties of wood utilized in Malawi are largely unknown. As a result, the exact quantity of wood is not known, however, the quantity of wood members required for our structure was estimated by assuming that the member spacing would be similar to that of the existing structure.

It was decided that a full concrete slab would be put in place, instead of a sole contour slab. This was done in order to reduce the invasion of termites on the structure, which are known to come from the ground and eat the wooden structures. In addition, it would reduce the need for organophosphates, which are chemical compounds that are considered more favorable than chlordane, as mentioned above, but also pose risks to human health and should not enter the food chain. However, this is a costly process, and alternative solutions for termite control would need to be found in the future.

Polystyrene costs were estimated from products available at a local hardware store, which to us seemed too expensive proportionally to the rest of the structure. Although it would be a very effective thermal insulation material over a long period of time, the initial capital costs were too high for this material to be included in our design. Therefore, an alternate source of insulating material, in this case straw, was considered because it is locally available and easily replaceable. From literature, we found that it would need to be twice as thick as the polystyrene material to obtain the same insulating properties (Rozis and Guinebault 1995), meaning a straw layer thickness of approximately 0.1m would be required. This choice of material triggered the need for a metal meshing at the bottom of the solar collector, in order to maintain the straw in place, as well as provide accessibility for maintenance and replacement.

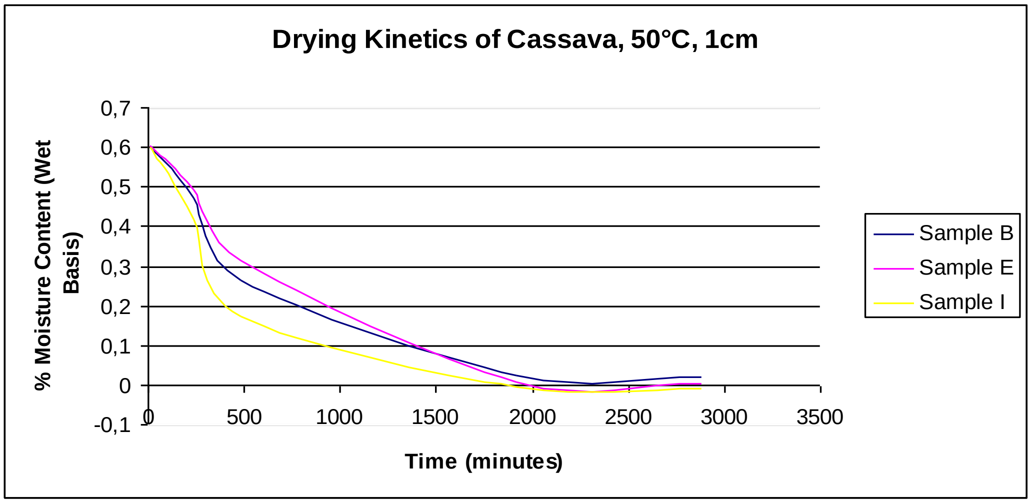
Finally, this structure is much more expensive than the previous one (+/- 4700$ for the new structure), while remaining in the ranges of prices acceptable for similar structures (1200-17000) (Rozis and Guinebault 1995). Overall, the main cost increases came from the concrete slab, the metal sheeting used for the solar collector, as well as the increase in the size of the structure which increased overall costs.

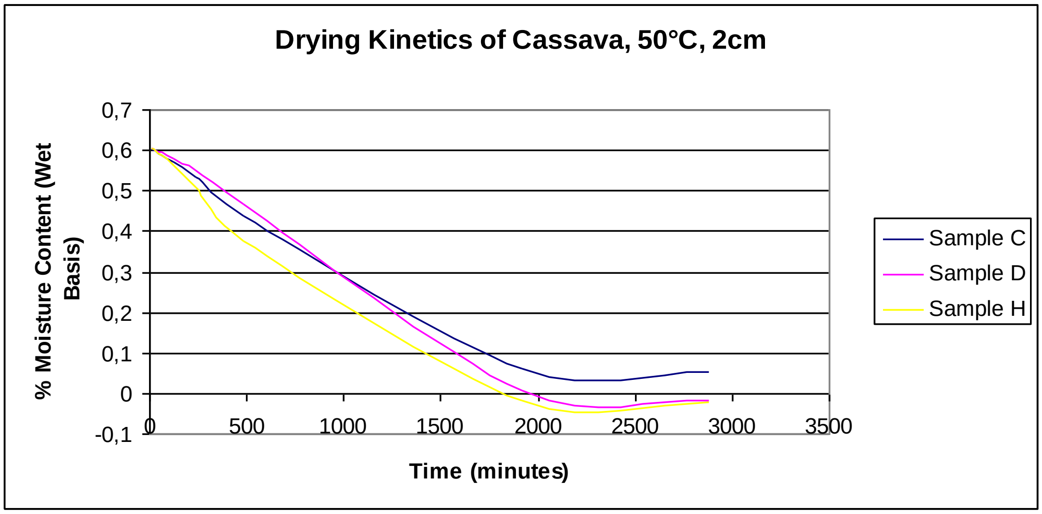
7 Conclusion

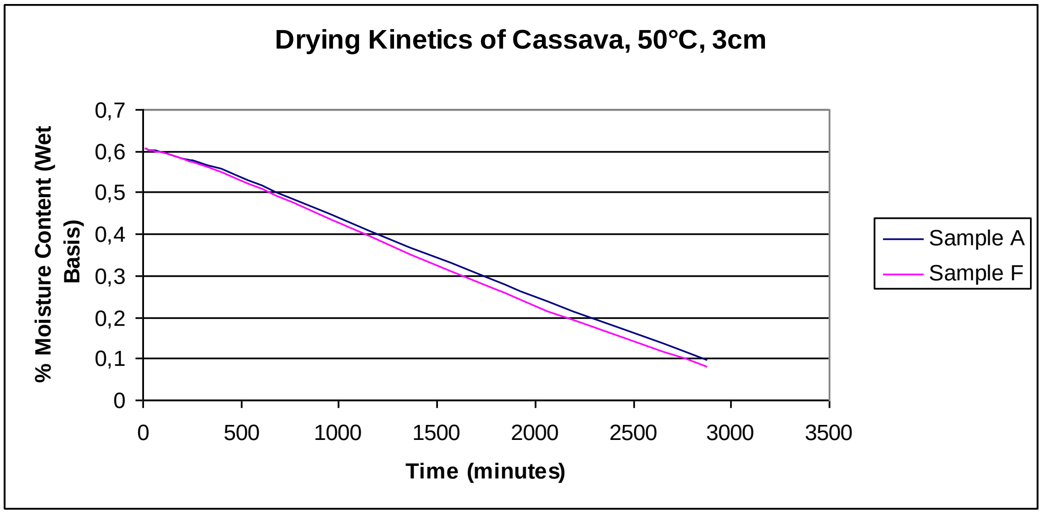
In conclusion, we successfully formulated a potential mixed mode natural convection solar dryer design for Chisemphere, Malawi using the resources available to us. We hope that the information contained in this document can be of use to people involved with the current cassava drying project on the ground including Graham Lettner and to future students in the Department of Bioresource Engineering who wish to undertake solar drying projects in the future.

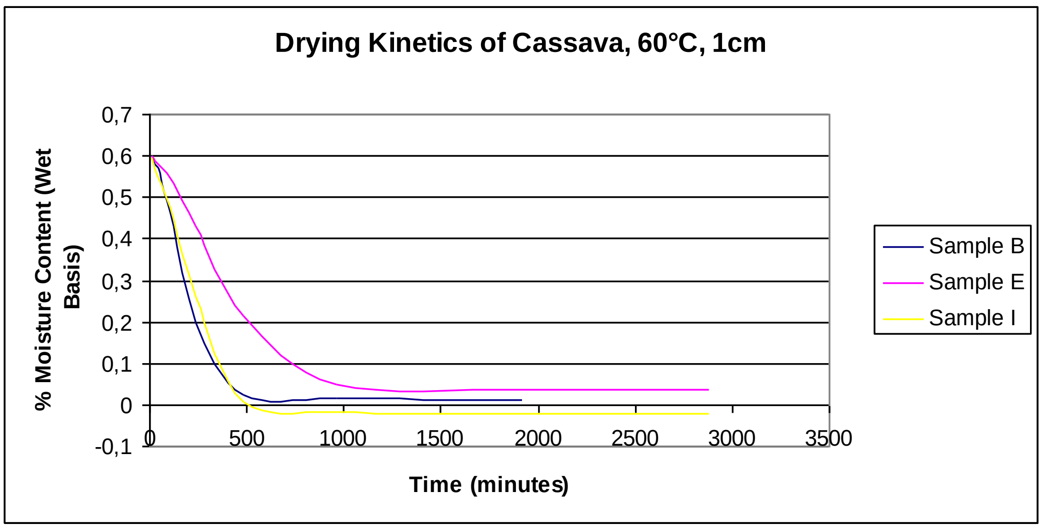
Appendix 1: Laboratory Experiment Results

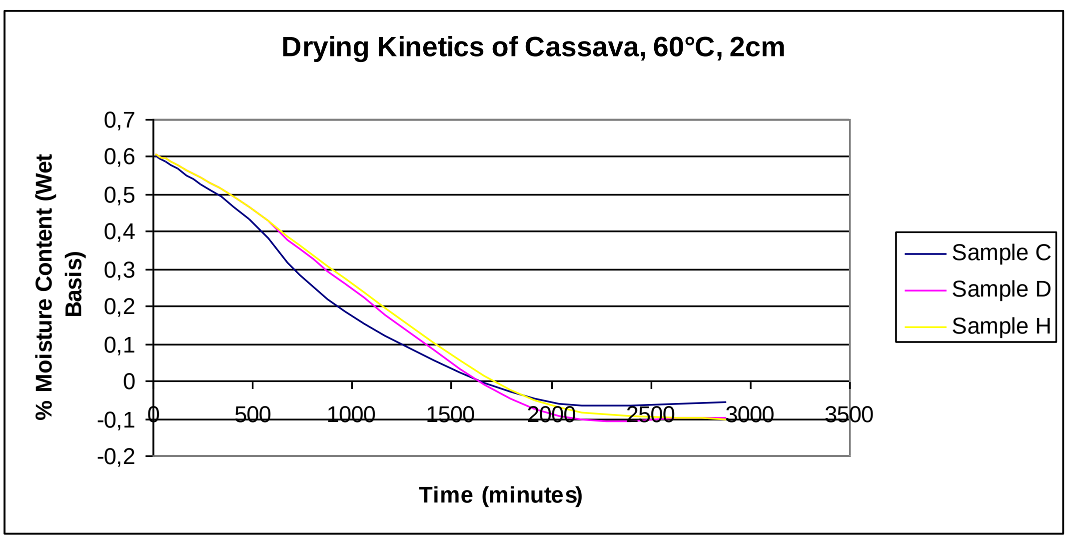
The following 9 graphs represent the different drying kinetics at different layer thicknesses and temperature, as the last 3 compare the effect of temperature on one sample location of each of the different thicknesses.

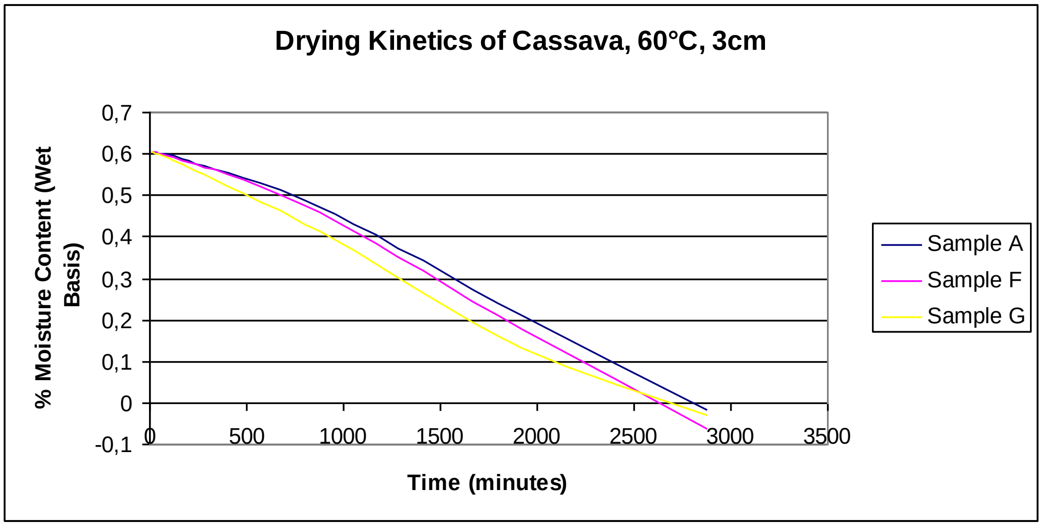


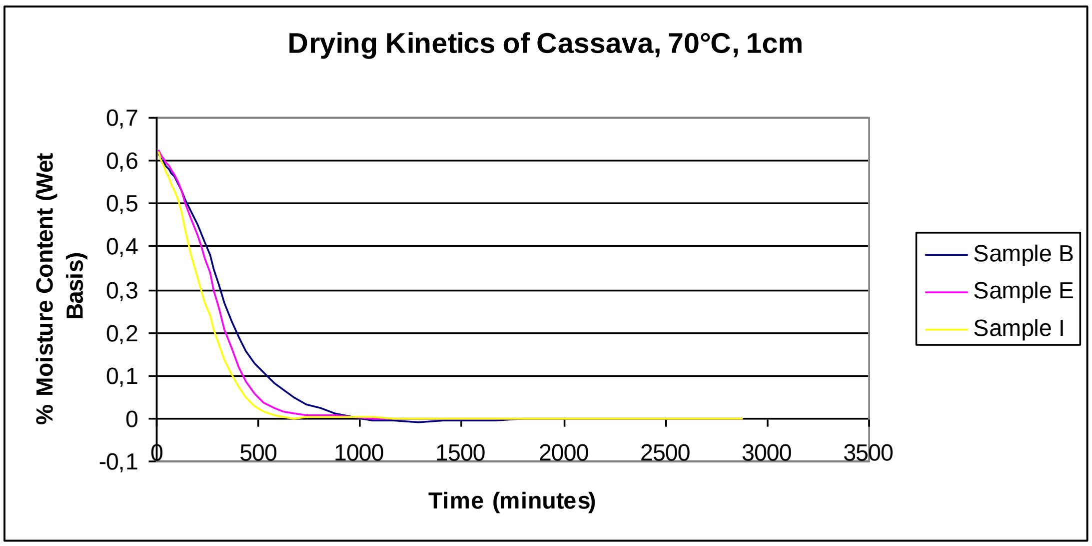


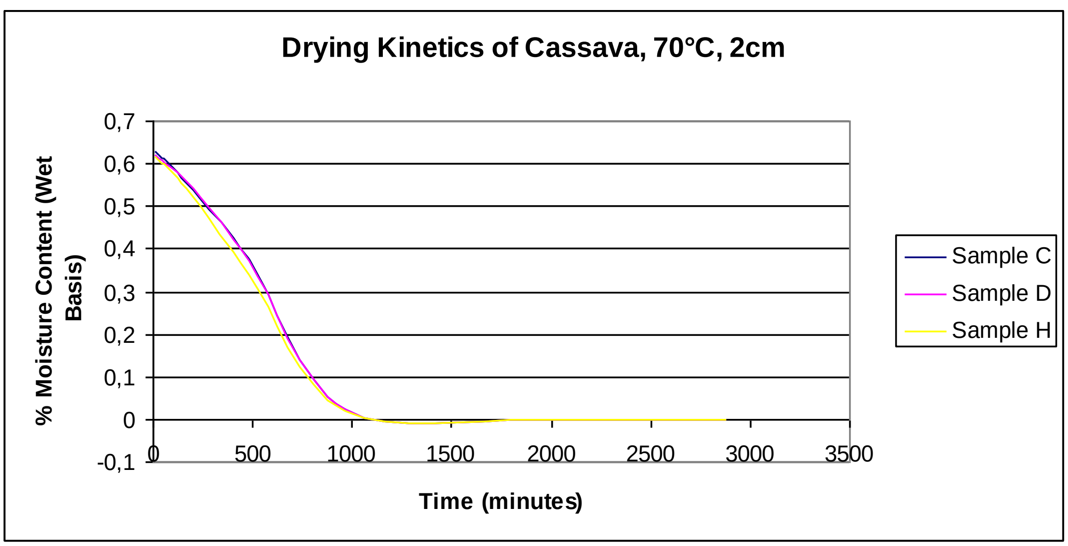

Drying Kinetics of Cassava, 50°C, 3cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
500
1000
1500
2000
2500
3000
3500
Time (minutes)
Sample A
Sample F

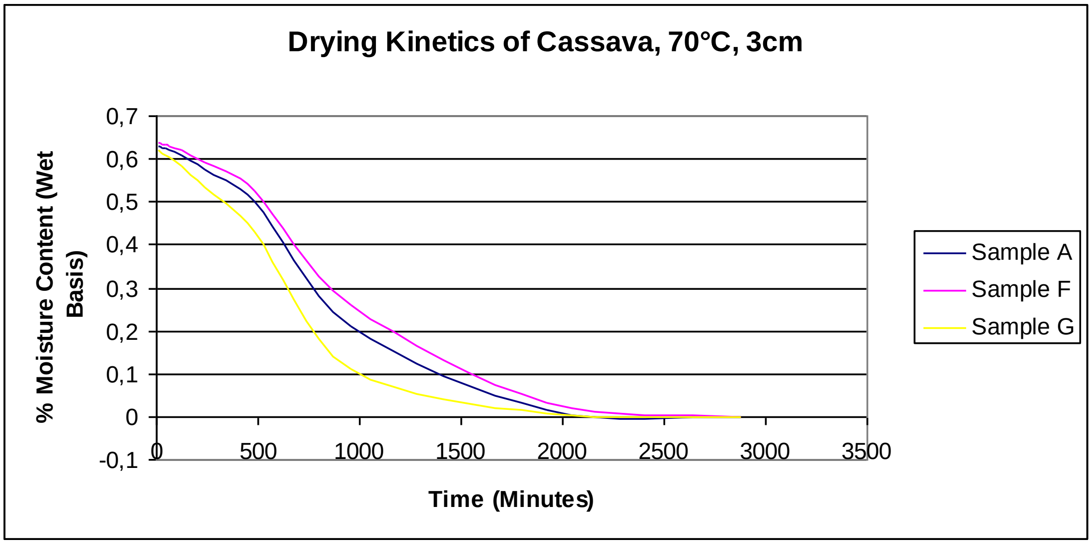

Drying Kinetics of Cassava, 60°C, 1cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
0
500
1000
1500
2000
2500
3000
3500
Time (minutes)
Sample B
Sample E
Sample I

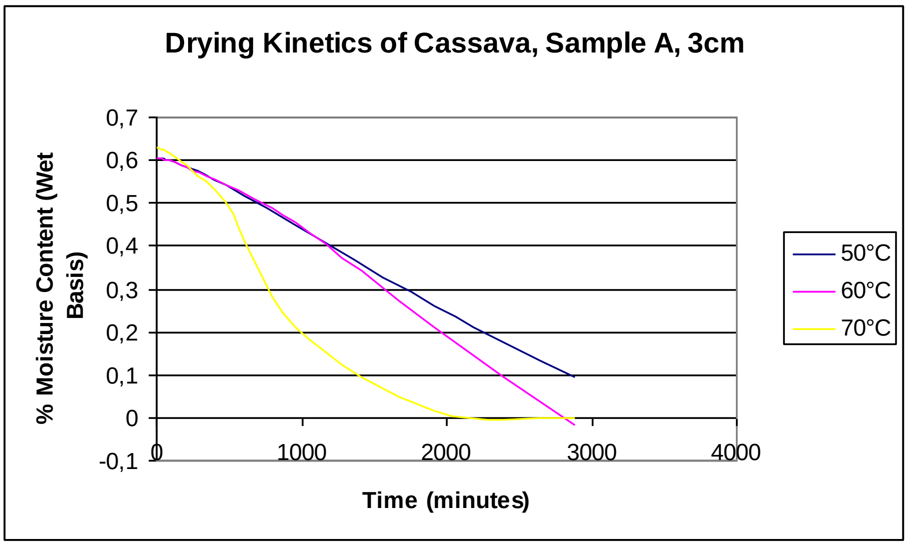

Drying Kinetics of Cassava, 60°C, 2cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
-0,2
0
500
1000
1500
2000
2500
3000
3500
Time (minutes)
Sample C
Sample D
Sample H

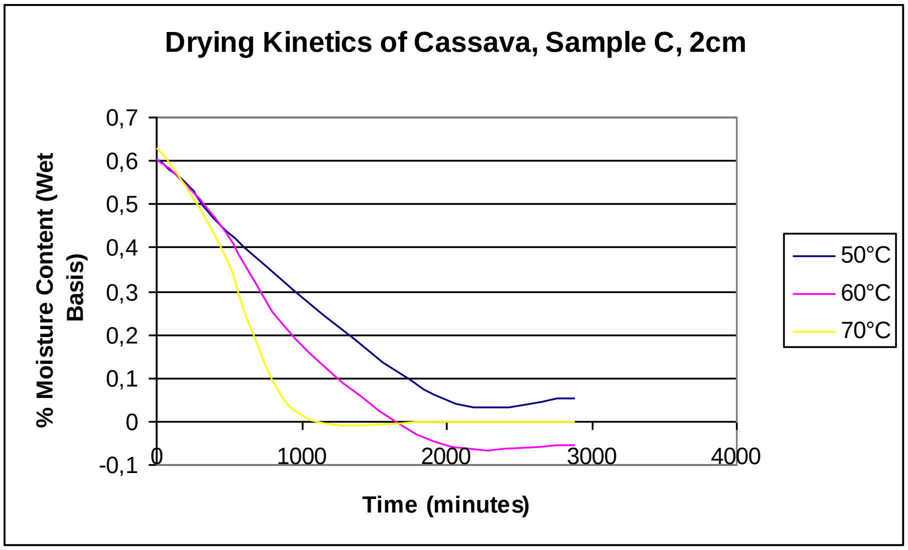

Drying Kinetics of Cassava, 60°C, 3cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
0
500
1000
1500
2000
2500
3000
3500
Time (minutes)
Sample A
Sample F
Sample G


Drying Kinetics of Cassava, 70°C, 1cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
0
500
1000
1500
2000
2500
3000
3500
Time (minutes)
Sample B
Sample E
Sample I

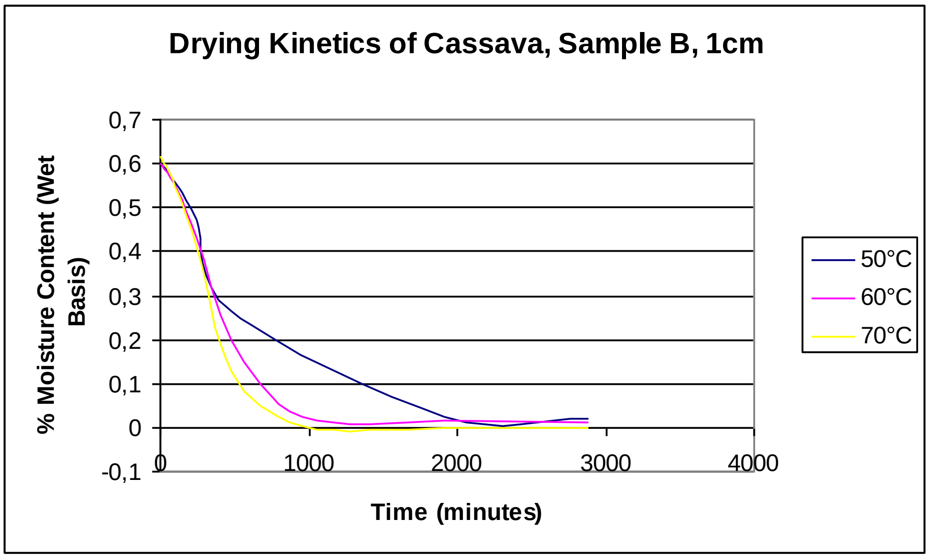

Drying Kinetics of Cassava, 70°C, 2cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
0
500
1000
1500
2000
2500
3000
3500
Time (minutes)
Sample C
Sample D
Sample H


Drying Kinetics of Cassava, 70°C, 3cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
0
500
1000
1500
2000
2500
3000
3500
Time (Minutes)
Sample A
Sample F
Sample G


Drying Kinetics of Cassava, Sample A, 3cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
0
1000
2000
3000
4000
Time (minutes)
50°C
60°C
70°C



Drying Kinetics of Cassava, Sample C, 2cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
0
1000
2000
3000
4000
Time (minutes)
50°C
60°C
70°C



Drying Kinetics of Cassava, Sample B, 1cm
% Moisture Content (Wet Basis)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
-0,1
0
1000
2000
3000
4000
Time (minutes)
50°C
60°C
70°C

Raw Results of Drying Kinetics Experiments: Mass(g) of Samples at Different Times, at 50°C

Sample											
	0 min.	5min.	15min.	25min.	45min.	60min.	120min.	240min.	480min.	1920min.	2880min.
A	353.73	352.9	352.28	351.58	350.03	348.64	343.72	331.47	304	188.23	153.91
B	102.44	101.2	100.15	98.87	96.54	94.72	88.81	76.5	54.8	41.34	41.17
C	176.3	174.9	173.95	172.72	170.49	168.57	161.94	148.67	123	74	73.29
D	221.43	220.6	219.87	218.82	216.51	214.59	207.58	193.65	164	87.84	85.69
E	132.37	131.3	130.21	128.94	126.31	124.24	117.04	102.57	76	52.39	52.2
F	286.76	286.1	285.51	284.79	283.24	281.84	277	265.97	243	149.02	122.77
G											
H	161.41	160.7	159.64	158.21	155.42	153.25	144.9	129.7	102	62.32	62
I	122.59	121.2	118.84	116.99	112.9	110.06	99.49	82.81	58.3	48.01	47.8

Raw Results of Drying Kinetics Experiments: Mass(g) of Samples at Different Times, at 60°C

Sample												
	0min.	5min	15min.	25min.	45min.	60min.	120min.	240min.	480min.	960min.	1920min.	2880min.
A	420.31	419	418	417.2	415.2	414	407.3	389.4	360.6	304.2	209.21	162.5
B	116.06	114	113	111	108.1	106	97.6	80.14	57.02	46.8	46.32	46.16
C	220.1	218	217	214.7	211.8	210	201.1	183.8	152.8	106.6	82.54	81.91
D	261.92	261	260	259	256.6	255	245.7	226.6	192.6	139.2	95.89	93.7
E	119.55	117	116	114.3	111.3	109	100.8	82.47	59.78	49.34	48.82	48.68
F	374.41	373	373	371.5	369.6	368	361.1	345.5	317.3	261.9	179.13	138.3
G	437.67	436	434	432.5	429.2	427	414.3	389.4	348.7	283.1	198.14	167.3
H	301.11	300	299	297.5	294.6	292	281.8	260.4	221.9	163.3	112.66	107.6
I	116.59	113	110	106.3	101.2	97.7	82.7	61.83	46.25	45.12	44.82	44.81

Raw Results of Drying Kinetics Experiments: Mass (g) of Samples at Different Times, at 70°C

Sample	0min.	5min.	15min.	25min.	45min.	60min.	120min.	240min.	480min.	1140min.	1920min.	2880min.
A	325.35	323.8	322.36	320.87	318.43	316.05	305	282.13	240.42	152.18	121.7	119.94
B	129.5	127.4	124.77	122.57	119.22	116.4	104.31	83.32	56.16	49.34	49.06	49.06
C	218.8	216.8	214.3	211.95	208.36	205.21	192.45	167.01	128.89	82.37	80.52	80.52
D	233.17	231.8	229.7	227.5	224.12	221.23	208.62	184.59	140.8	90.37	88.07	88.06
E	127.53	125.7	122.98	120.74	117.03	113.96	100.26	74.75	49.89	47.19	47.04	47.04
F	335.61	334.6	333.43	332.24	330.08	328.05	318.31	296.4	254.96	163.33	125.12	121.07
G	342.16	340.4	337.62	335.18	330.82	327.13	311.09	277.39	226.86	145.35	130.3	129.31
H	238.33	237.1	234.7	232.57	228.86	225.74	211.44	183.18	138.36	92.96	91.23	91.23
I	136.83	133.9	129.22	125.2	119.65	114.99	97.6	69.38	52	50.81	50.59	50.59

Appendix 2: Original Material Costs

A Summary of the Quantities and Cost of Various Materials Used in the construction of the Existing Drying Structure

ITEM	QUANTITY	UNIT PRICE (Malawian Kwacha)	TOTAL PRICE (Malawian Kwacha)
Bricks (9”x4.5”x 2.5”)	1000No	2.5	2 500
Cement (OPC)	5 pockets	2 500	12 500
Sand (river)	2 tonne	700	1 400
Timber (3” x2”)	60No.	450	27 000
Timber (2” x2”)	25No	250	6 250
Wire nails (2”)	4 Kg	300	1 200
Wire nails (4”)	5 kg	300	1 500
Wire nails (1”)	2 kg	300	600
Greenhouse sheeting (250 micron)	2 rolls	26 500	53 000
Aluminum wire mesh (45 micron)	2 roll	13 000	26 000
T and G (4”)	45 No.	600	27 000
Nylon ropes (0.25”)	30 m	250	7 500
Chlordane (gulf)	1 litre	2 500	2 500
Timber strips(40mm x20mm)	60No	450	27 000
Quarry stone	1 tonne	1 500	1 500
Labour			
Grand total			**237 450**

Conversion: 140 Malawian Kwacha = 1 Canadian Dollar

Appendix 3: Design Procedure and Calculations recommended by Rozis and Guinebault (1995)

Rozis and Guinebault (1995) laid out 24 preliminary questions that need to be answered in order to have the basic information necessary to design a solar drying structure. The majority of these questions and their results for our project are listed below. They were initially performed in order to form the basis of our dryer design, however, as can be seen below, the results from these calculations were unreasonable for our project and resulted in our using the design process outlined by Forson, Nazha et al. (2007) instead.

Questions:

1. *What product is to be dried and what are the objectives of this drying process?*

   The product to be dried is cassava and the main objectives of the drying process are to dry the product to a moisture content of 15% within a 24hour period while protecting the product from contamination by dust and debris.

2. *What quantity of fresh product should the dryer be capable of processing on average per day?*

   In the future, it is projected that 600kg of cassava will arrive at the processing facility on a weekly basis. To design for the worst case scenario we will assume that all of the cassava will arrive at the facility in one day. As a result, the dryer should be capable of processing 600kg of cassava on an average day. Also, such a scenario opens up potential for other crops to be dried in the structure when it is not being used to dry cassava.

3. *How much time can the product remain undried before it starts to degrade?*

One of the most significant constraints when dealing with cassava is that the produce can begin to deteriorate as soon as 24 hours after harvest and if the cassava is not kept under conditions favourable (25 to 35 deg C, 85 to 95 % RH) they often become unacceptable for human consumption within 2 to 3 days(Wenham 1995).

4. *What mass of water must be removed from the product?*

   The mass of water that must be extracted is found using the following equation from Rozis and Guinebault (1995):

$$M_e = \frac{(m_i - m_f)M_i}{100 - m_f}$$

Where

M_e is the mass of water to be removed from the product [kg]

M_i is the mass of product to be dried (after it has been pelleted and pulverized) [kg]

m_i is the initial moisture content the fresh product [%]

m_f is the final moisture content the dried product [%]

Bokanga (n.d) indicates that 15% moisture content is the ideal final moisture content for cassava. Our drying kinetics experiments indicated that the initial moisture content of cassava is approximately 60%, which is consistent with the cassava moisture contents found in the literature (Monroy-Rivera et al. 1996). Also for the purpose of this calculation we will take the mass of product to be dried as 600kg, as described above. As a result, the mass of water to be removed from the product is **317.65kg of water**.

5. *What must the duration of drying be?*

Because it takes approximately one day to peel the cassava by hand and pulverize the material using a machine located on site and the cassava with significantly degrade within two to three days, as mentioned previously, it is imperative that the product be dried as quickly as possible. This means that all of the cassava should ideally be dried within a 48 hour period inside the solar dryer to prevent significant degradation.

6. *What will be the speed of water removal from the product?*

$$V_{em} = \frac{M_e}{T_s}$$

Where

V_{em}= average speed at which water must be removed from the product [kg/hr]

M_e= masse of water to be extracted from the product [kg]

T_s= ideal duration of drying (hr)

The response to question 4 above indicates that 317.65kg of water is to be removed from the product and the response to question 5 states that the ideal duration of drying is 48 hours. As a result, the equation above indicates that the speed at which water must be removed from the product under these conditions is 6.62 kg/hr. However it would be more conservative to assume that water is only being removed during the 12 hours of sunlight per day in Malawi and as a result the speed of water removal would be **13.24 kg/hr**.

7. *What temperature must the air be when it reaches the product to be dried?*

Rozis and Guinebault (1995) recommend that the temperature of the air reaching the product during the first stages of drying should be maintained at 10^{o}C above the maximal permissible temperature the product should experience. The maximum air temperature recommended for cassava is 70^{o}C (Forson, Nazha et al. 2007). This is recommended because the large amounts of water being evaporated during these first stages will cool the product. However, because the cassava will be exposed to direct sunlight in the solar dryer, we will aim to provide air that is at the maximal permissible temperature the product should experience, to ensure none of the crop is damaged. Then during the last stage of drying, it is recommended that the temperature inside the greenhouse be slightly less than the maximal temperature. This coincides well with the timing of our cassava drying process since the last stage of drying will likely occur in the evening, when incoming air temperatures will be lower, since the drying is to occur in 24 hours. However, our lab experiments indicated that drying cassava at 60^{o}C minimized browning of the product while also drying the cassava at an acceptable rate so for the purposes of this project we will utilize 60^{o}C as the ideal drying temperature.

8. *What are the evaporative capabilities of the air?*

Three main factors influence the ability for air to remove water from a food material; the amount of water vapour already contained in the air, the pressure of the air and the air's temperature(Rozis and Guinebault 1995). As indicated in our report the harvest of cassava is primarily done in October, November and December, which are part of Malawi's rainy season. The average temperatures and relative humidities of air during those months for Chisemphere, Malawi, according to a database compiled for NASA by Stackhouse and Whitlock (2008), are shown in Table A1 below.

Table A1: Average Monthly Temperatures and Relative Humidity for Chisemphere, Malawi

	Oct	Nov	Dec
Monthly Averaged Air Temperature At 10 m Above The Surface Of The Earth (°C)	25.3	24.7	22.8
Monthly Averaged Relative Humidity At 10 m Above The Surface Of The Earth (%)	43.9	55.5	73.3

Source: (Stackhouse and Whitlock 2008)

The air conditions in December are least favourable for drying since the air during that month has the lowest temperature (22.8^{o}C) and highest relative humidity (73.3%). A standard psychrometric chart (Bhattacharjee and ASHRAE Publications 2007) indicates that air under those conditions contains 13g of water per kg of dry air. If we assume that the air inside the structure has uniform temperature of 60^{o}C and that the relative humidity of the air when it leaves the structure is 75%, as recommended by Dr. Raghavan, then the amount of water it will contain when exiting the structure is 100g of water per kg of air (Earle 1983).

9. *What quantity of the products water can be removed with a meter cubed of air?*

In an ideal world the water that would be removed from a food material in a given air environment would be equal to the amount of water the amount of additional water that air can hold to the point where it becomes saturated, as was described in question 8. However, as was pointed out by Rozis and Guinebault (1995), in reality air passing over a material will not typically absorb all possible moisture until it reaches saturation as a result of multiple factors. For one, water inside a food material is not the same as free water and therefore there will be some resistance to water uptake from the food material. Furthermore, some of the heat in the air will be lost to the exterior and will not contribute to removing water from the food material. As a result of these and other factors a value for drying efficiency, η_d, is typically added to calculations to determine the effective amount of water that can be extracted by a m^3 of air within the system. The resulting formula is as follows:

$$q_{se} = \rho_{air} * (x_m - x_a) * \eta_s$$

Where

q_{se}= average amount of water that can be extracted per meter cubed of air [g/m^3]

ρ_{air}=bulk density of dry air ≈1.2 kg/m^3

x_m=average moisture content of air exiting the dryer [g/kg dry air]

x_a=moisture content of air entering the dryer [g/kg dry air]

η_s=drying efficiency

The values of the drying efficiency constant are dependent on the product being dried, the moisture content of the product and the type of dryer being used. Madhlopa and Ngwalo (2006) found the efficiency of a solar drying to be approximately 15%, while they state that this drying efficiency can vary depending on the type and initial moisture content of the product being dried, values particularly related to cassava and our design conditions are unavailable in the literature. As a result, we will assume that this efficiency applies to our context. Using this value and other values mentioned above, the average water removable is found to be 18.0 g/m^3.

10. *What is the required air flow in the dryer?*

$$Q_s = 1000 * \frac{V_{em}}{\rho_{air} * (x_m - x_a) * \eta_s}$$

Where

Q_s= desired air flow [m^3/hr]

V_{em}= speed at which water must be removed from the product [kg/hr]

ρ_{air}=bulk density of dry air ≈1.2 kg/m^3

x_m=average moisture content of air exiting the dryer [g/kg dry air]

x_a=moisture content of air entering the dryer [g/kg dry air]

η_s=drying efficiency

Using the above equation the required airflow is 735m^3/hr.

11. *Can this required air flow be supplied without additional equipment, like solar chimneys or ventilation systems?*

Rozis and Guinebault (1995) advises that natural convection can adequately meet the drying needs of a given product if the desired air flow determined in question 10 above is less than 20m^3 per hour. While this is far below the air flow required for our system, it should be noted that numerous characteristics can be incorporated into our design to facilitate water removal via natural convection. These characteristics include having a large height difference between the air entrance and exit, ensuring a large temperature difference between the entering and exiting air and ensuring that the air speed within the structure is not so fast that there is insufficient time for moisture exchange between the product and the air (Rozis and Guinebault 1995). However, because our air flow requirements are so much higher than 20m^3 per hour, we must explore the possibility of incorporating peripheral structural additions to ensure adequate airflow.

12. Is a solar chimney an appropriate addition?

Rozis and Guinebault (1995) recommends solar chimneys for systems that require air flows of 20 to 60 m^3, above which is it recommended that ventilation systems be installed. While our system requires much greater air flows that $60m^3$, because of the lack of available electricity and substantial funding to supply fuel for a diesel based system, the incorporation of a solar chimney into our design will play a crucial role in motivating air movement through the structure by natural convection.

13. At what point should a ventilation system be considered?

As was mentioned above, when air flows of $60m^3$ or more are required a forced ventilation system should be put in place to ensure adequate airflow within the structure. In reality, it would be unrealistic to implement a forced ventilation system in Chisemphere, Malawi indicating that these calculations yield a result that would be impractical to put into place in Malawi.

14. How much energy is required for the evaporation of water in the system?

As was mentioned earlier, ideally the air temperature should be at the 60 degrees Celsius once it reaches the product in order for the cassava to dry under ideal conditions. In order to determine the power input required create those conditions we can use the following equation:

$$P_n = \rho_{air} * \frac{(h_s - h_a)}{3600} * Q_s$$

Where

Q_s= desired air flow [m^3/hr]

ρ_{air}=bulk density of dry air ≈1.2 kg/m^3

h_s and h_a: the energy contained in the air entering and exiting the dryer, respectively [kJ/kg]

P_n= Power required for the drying [kW]

3600: a conversion from hours to seconds

The power required can also be approximated by the following equation:

$$P_n = \rho_{air} * Cp_{air} * \frac{(T_2 - T_1)}{3600} * Q_s$$

Where

P_n= Approximation of the power required for the drying [kW]

Cp_{air}= specific heat of air [J/kg/^{o}C], which is approximately 1030 J/kg/deg C

T_1 and T_2: Temperature the air entering and exiting, respectively, the solar collector, which preheats the air coming into the dryer [^{o}C]

For our drying conditions T1= 22.8 degrees and T2= 60 degrees and as a result the power required to heat the air is 9395 kW.

15. *How much energy must be supplied to the air?*

    The energy that must be supplied to the air is equal to the power found above multiplied by the duration of drying.

$$E_n = P_n * t_s$$

Where

E_n= Theoretical energy required [kWh]

t_s= Duration of drying [h]

P_n'= Approximation of power required for drying [kW]

The resulting energy required based on the above calculations is 225 500kWh

Heat losses from the system and efficiencies of heat transfer should also be considered.

$$E_{actual} = \frac{E_n}{\eta_{thermal}}$$

Where

E_n= Theoretical energy required [kWh]

E_{actual}= Actual energy required [kWh]

$\eta_{thermal}$= Thermal efficiency of solar collector

The thermal efficiency is typically determined through experiments but if we assume losses to be 50%, the energy required is 451 000 kWh

16. What surface of solar energy capture is necessary?

$$A = \frac{P_n}{\eta_c * G_n}$$

Where

A= the surface area of the solar collector [m^2]

P_n= Power required for drying

G_n= Strength of available solar radiation [kW/m^2]

η_c= efficiency of solar capture (typically ranges from 0.4 to 0.6)

Using 5.83 kWh per m^2 per day as the value of available solar radiation (Stackhouse and Whitlock 2008) and an efficiency of 0.5, in combination with the results of above calculations, the surface area required to capture the solar energy necessary is approximately 154 700m^2. This means that if a square structure were to be built, each side would be over 390m in length. It is clear from the results of this last question that this calculations yields results that are unfeasible for our project.

Appendix 4: Pressure drop and height of hot air column calculations according to Forson, Nazha et al. (2007)

Pressure Drop

The pressure drop due to resistance to air flow through a packed bed of food material can be found using Equation 16

$$u = a\left(\frac{\Delta P_B}{h_L}\right) \qquad [16]$$

Where

u is the superficial air velocity, which can be assumed to be equal to the maximum velocity at the exit of the air-heater

a is a constant

ΔP_B is the pressure drop across the bed

h_L is the bed thickness

According to Forson this equation can also be applied to systems where air moves by natural convection through thin layers of cassava chips, where hL≤0.2m. Under such situations a=0.465m^3 s/kg. Also from above u=0.3m/s and our h_L is 0.02m, so the resulting pressure drop is 0.013Pa, if these calculations applied to our design. The total pressure drop of the system, ΔP_T, is typically twelve times the drop across the bed, so in this case it would be 0.156Pa.

Height of the Hot Air Column

The last dimensioning calculation for designing this solar dryer is to determine the minimum height of the exit vents above the primary collector inlet that will allow moist air to escape to the atmosphere by natural convection. This dimension is commonly called the height of the hot air column and is determined based on the following assumptions, as listed by Forson, Nazha et al. (2007):

1) The dryer is working under steady state conditions

2) The depth of the drying bed, h_L, is small compared to the height of the hot air column, H

3) The whole structure is air tight and ambient air enters through the inlet and the moist warm air leaves via the vent in the chimney

4) The steady state mean values of temperature and density of the hot air inside the dryer are T_o and

ρ*, respectively.

It is then possible to apply Bernoulli's equation to the system, as was done by Forson, Nazha et al. (2007), and simplify to Equation 17 to get:

$$H = \frac{\Delta P_T}{g(\rho_a - \rho^*)} = \frac{\Delta P_T}{g(1/T_a - 1/T_o)P_a / R_a} \qquad [17]$$

Where

ΔP_T is the total pressure drop of the system
g is acceleration due to gravity, which is 9.81m/s^2
P_a is the atmospheric pressure, which is 101325Pa
R_a is the specific gas constant [286.9 J/kg K]
T_a is the ambient temperature [295.8K]
T_o is the temperature of drying air leaving the air heater [305.55K]

In this case ΔP_T = 0.156Pa and the resulting H is 0.417m. This value for H is relative small compared with other solar dryers because our drying layers are so thin.

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