DEVELOPMENT OF A NATURAL CONVECTION DRYER FOR USE IN DEVELOPING COUNTRIES

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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INTRODUCTION

There is a vital need for a massive increase in food production in developing countries of the world, and especially in the Third World. This is due to the fact that the developing countries as a whole, with over 70 percent of the world's population, account for not much more than 40 percent of its agricultural production. In realization of this fact, many countries in the Third World have launched various schemes to increase food production through efficient cultivation, using high yielding varieties, fertilizers, insecticides and good crop husbandry. But necessity for establishing proper post-harvest systems has not received sufficient attention. The cost of importing sophisticated storage facilities from developed countries is high, and most farmers, particularly the small scale farmers, in developing countries cannot afford to install, maintain, and operate these sophisticated facilities.

Certainly all efforts to increase food production would be for nought if grain losses from harvest, through storage, to the consumer are not reduced to the bare minimum. Types of grain losses include: loss of weight, loss in food value, quality reduction, monetary loss, seed loss and loss of good will by the producers. By far the greatest loss occurs during storage. A season's harvest can be lost entirely if not properly handled, dried and stored. Grain must be harvested at the right time and stored at correct moisture content to prevent attacks by insects, rodents, and molds and other microorganisms.

As mentioned earlier, losses due to bad storage are greater than any other type of loss. To minimize post harvest losses and to preserve grain quality, the grain must be stored at the correct moisture content depending on the environment and storage facility available. Effective drying of these grains to remove some moisture becomes very important.

Unfortunately, however, not enough attention has been given to the problem of grain drying and storage in developing countries. To support this contention, at a recent effort to appraise the situation of grain storage in developing countries, it was only with difficulty that a few data on grain storage capabilities, locations, and types could be found to write the report (Pedersen, 1975 "Status of Grain Storage in Developing Countries" Special Report No. 3. Food and Feed Grain Institute, Kansas State University). Effective drying also makes possible increased production through multiple cropping where the off-season crop is harvested in humid weather.

In the rain forest areas of the developing countries under humid conditions, there are usually a few weeks of dry period between the two rainy seasons. This dry period is usually not long enough to dry grain on the field for safe storage. Therefore, it is necessary that some source of added heat energy be provided to remove moisture from wet grains.

Efforts in developed countries on grain drying have reached a reasonably satisfactory stage, and sophisticated dryers can be found dotted all over the countries. Attempts have been made by some of these countries to introduce these sophisticated dryers to farmers in developing countries but due to the high cost of installation, maintenance, operation and lack of technological knowledge and good management, their use has become uneconomical for such farmers. In order to reduce cost per farmer, and eliminate some of these limiting factors, some farmers in the developing countries have formed cooperative groups to obtain these sophisticated dryers, but difficulty in obtaining spare parts at appropriate times, again, has made this good venture uneconomical for the farmers. One can find broken down fans, dryers, generators, and damaged as well as rusty metal silos in the cooperative Agro-centres.

The "Brook" dryer (Brook, 1964), which is basically a batch dryer, is simple enough to operate and to build on a farm, using available local building materials. The farmer and his family can construct these dryers themselves to avoid having to pay other workers. The dryer has a flue as a heat source and utilizes the buoyancy force of natural convection as a driving force to move heated air through the grain without any mechanical device.

It is, therefore, intended to modify this simple and inexpensive natural convection dryer to give better drying performance for use in the developing countries.

LITERATURE REVIEW

Life would be short and worthless if there were no food to feed the population of the world all the year round. In as much as weather conditions prevent production of food crops all the year round in most countries, ways have to be found to preserve grains harvested for use during the months that these grains are not produced. This is why drying of grain is very important to prevent germination of seeds, to retain maximum quality of the grain, and to store the grain at a moisture content that would not suit the growth of bacteria, fungi, and other microorganisms.

No matter what method of drying is employed, the process of drying must be fast and effective. There are two types of drying, natural and artificial.

In the tropical and subtropical countries, advantage is taken of the solar heat to dry grain before and after harvest, especially in the arid areas. This drying method and other local methods and procedures are fundamentally unsound because of facility design, lack of control of incoming field infestation and rodents, lack of protection from rain, nonuniform drying, etc. Drying air temperatures may have a significant effect on grain quality. Excessively high kernel temperature in corn and rice causes increased breakage, stress cracking, kernel discoloration, and leads to a decrease in milling yield and protein quality.

Storage losses under tropical conditions can be as high as 35 to 50 percent at the farmer level (Hall, 1969). The problem of storing grain is particularly more serious in the humid tropical areas. Nowadays, farmers have realized that effective drying and storage can result in a higher income for them since they can delay selling their harvest till market prices are high.

1. Drying Theory

Relative Humidity and Moisture Content Relationship

For each type of grain there is a definite relationship between grain moisture content and relative humidity of the air. Equilibrium moisture content for a given relative humidity changes slightly with changes in air temperature. Grain and air are in equilibrium when the vapor pressure of the moisture in the grain is equal to that in the air; the net flow of moisture to or from the grain is zero and its moisture content remains the same. The r.h. (relative humidity) is the amount of water vapor pressure present in the air, expressed as a percent of the total amount of water vapor pressure which the air is capable of holding at any particular temperature.

Many researchers have looked into the relationship between the equilibrium moisture content of grain and the relative humidity of ambient air at a constant temperature, and have developed isotherm equations.

For example:

(i) $1 - rh = e^{-CTM_e^n}$ Hendersen (1966)

(ii) $\ln(rh) = -\frac{A}{RT} e^{-BM_e}$ Chung (1967)

where

rh = relative humidity in decimal

M_e = equilibrium moisture content in percent (db)

T = absolute air temperature in Rankine

R = universal gas constant

C, n, A and B are all constants

Gough and Bateman, (1977) extracted the results obtained by many researchers on the relationship of moisture content and relative humidity for many varieties of tropical produce such as maize, sorghum, wheat, etc. They are of the opinion that there is considerable evidence that oven determination of moisture contents at high temperatures for long periods introduces errors. In tropical storage management the usual requirement is the deduction from an isotherm of the moisture content for safe storage. This is generally accepted as corresponding to 70 percent equilibrium relative humidity. Since mold growth does not begin precisely at 70 percent R.H., an error of ± 3 percent can be tolerated.

Pixton and Warburton (1971) investigated the relationship between moisture content and equilibrium relative humidity obtained at different temperatures of 15°, 25°, and $35^{\circ}C$ for five oilseeds of economic importance, namely soya beans, sunflower seed, linseed, groundnuts and copra. The cereal grains are similar to each other but differ widely from the oil seeds. The relation between equilibrium relative humidity and moisture content of oily seeds is closer to that of cereals if the moisture content is expressed on an oil-free basis than when expressed on a weight basis including the oil.

Effect of Temperature on Drying

The temperature reached by the grain is important, not the temperature of the drying air. If grain is overheated, i.e., if the temperature of the air passing through the grain exceeds the recommended temperature, the germ of the grain can be killed, the nature of the chemical constitutents of the grain is changed, and the endosperm can be cracked. In fact, changes due to overheating can ruin grain for many uses. It is, therefore, important to follow the dryer manufacturer's recommendation when drying grains.

Bartsch and Finner (1976) investigated low temperature grain drying in an artificially reproduced environment. They stated that low temperature drying is an accepted grain conditioning method, but it does have limitations. Because of low airflow rates and small quantities of supplemental heat used, it may take several weeks to dry a deep bin of grain. Ambient air conditions obviously play a major role in determining the rate of moisture removal. In the experiment it was found that 27 percent moisture corn could be dried at low temperatures at air flows of from 3.2 - 4.6 cfm/bu. Thirty percent corn could likewise be conditioned, but up to 75 percent greater airflows would be needed.

The importance of air movement in drying processes whether by natural or artificial method cannot be overemphasized. The air carries heat into the system to evaporate moisture and then carries the evaporated water out of the system. Grain resists movement of air through it and the amount of resistance depends on the moisture content of the grain. In resisting air movement, a pressure drop develops as a result of the energy lost through friction and turbulence. The pressure drop for airflow through any product depends on the rate of airflow, the surface and shape characteristics of the product, the number, size, and configuration of the voids, the variability of particle size, and the depth of the product bed. Shedd (1953) found that corn which contains 20 percent moisture or more has less resistance to a given airflow rate than the same corn after it has been dried. In contrast Patterson (1969) and Mathies (1956) found that the pressure drop through corn increases with an increase in moisture content.

Pierce and Thompson (1975) developed a mathematical model for predicting air pressure patterns and airflow paths in round conical shaped piles of grain. The air pressure patterns were obtained by following the procedure used by Brooker (1961, 1969) for rectangular shaped bins and modified for long triangular-shaped piles of grain by Jindal and Thompson (1972). Jindal and Thompson's pressure distribution and flow path models were modified for application to conical-shaped piles. The results showed that increasing the pile base diameter with a given duct-diameter ratio increases the total airflow, while an increase in the angle of repose has little effect upon the total airflow rate. The resistance to airflow of each grain type (based on Shedd's data) also has an effect upon the system performance. Increasing duct size affects airflow distribution and causes an increase in airflow along the ground, where spoilage is most likely to occur.

2. Drying of Grain

In the drying process, energy in the form of heat is required to convert water into water vapor. It is, therefore, necessary to heat air flowing through grain since hot air can hold more water than cooled air, and the rate at which drying can take place will thus be affected by the temperature of the surrounding air and dependent on the amount of water vapor in the air. When the air is heated, its relative humidity reduces and the amount of water vapor it can absorb is increased.

Allen (1960), Hustrulid (1959), and Simmonds (1953) are nearly unanimous in observing that small grains exposed in thin layers (a layer one kernel deep) dry according to the following equation:

$$\frac{M - M_e}{M_o - M_e} = ae^{-kt}$$

where

M_o = initial moisture content, percent (d•b)

M_e = equilibrium moisture content, percent (d•b)

M = moisture content after a time t, percent (d•b)

a = constant, dependent on particle shape

t = time, hour

k = drying constant, $hour^{-1}$

The above equation indicates that the drying rate is proportional to the difference between the moisture content of the material, and its equilibrium moisture content is a function of the state characteristics of the drying air and, therefore, is constant, if the air temperature and relative humidity are constant. Thus, the drying rate falls with time since the moisture content decreases with time.

Henderson and Pabis (1961) studied basic thin layer drying at various temperatures and reviewed comparable published data for maize and other grains. The analysed data were resolved into a mathematical relationship that is statistically reliable. The results provide additional evidence that the drying mechanism is diffusion.

3. Evaluation of Energy Required

The heat of vaporization of cereal grains is defined as the energy required to vaporize moisture from the product. Equilibrium moisture content curves furnish the data necessary to calculate the heat of vaporization for moisture. The energy required to vaporize water from a cereal grain is dependent upon its moisture content and temperature. The lower the moisture content and the temperature, the higher will be its heat of vaporization. Othmer (1940) developed the following relationship for calculting the heat of vaporization of a product such as grain:

$$\ln (r.h.) = \frac{h_{f_{g_1}}}{h_{f_{g_2}}} + q$$

where

$h_{f_{g_1}}$ = heat of vaporization of adsorbed grain moisture

$h_{f_{g_2}}$ = heat of vaporization of free water

q = a constant depending on the product and temperature

(r.h.)= relative humidity of air

Othmer gave plots of equilibrium moisture content data for shelled corn desorption. He concluded that at low moisture contents, as much as 25 to 35% more energy is required to remove moisture from cereal grains than from a free water surface.

Other researchers have considered this problem of determining the energy utilized in vaporizing grain moisture.

Chung-Pfost (1967) came up with the following equation:

$$H_D = R \left(\frac{T_1 T_2}{T_2 - T_1} \right) \text{Ln} \left(\frac{P_2}{P_1} \right) / 18$$

where

H_D = heat of adsorption or desorption Btu/lb

R = constant, taken as 1.98

T_1 = first air temperature for drying grain in ^oR

T_2 = second air temperature for drying grain in ^oR

P_2 = vapor pressure of grain at Temperature T_2

Woodforde (1965) stated that the utilization of heat improves with a decrease in the airflow rate and that this is most marked at the lower temperatures at the range of drying conditions studied with 6 inch deep-beds of barley, i.e. the temperatures of 110°, 150°, and 190°F and the airflows between 14 to 70 cfm/bu. He also mentioned that mixing or turning the grain bed at intervals during the period of drying showed a decrease in the final moisture content gradient.

Morey, Gustafson, Cloud, and Walker (1978) worked on energy requirements for high-low temperature drying. They considered the effect of high-temperature drying followed by in-bin cooling and low-temperature drying. Low-temperature treatments included ambient air drying starting at three moisture contents, solar supplemented drying and drying during off-peak hours. They also considered energy requirements by conventional high-temperature drying with in-dryer cooling.

They found that combination of high-temperature, low-temperature drying significantly reduced propane energy requirements for drying corn. Secondly, they found that total energy use for drying corn was significantly decreased in most cases. Thirdly, in-bin cooling increases dryer capacity. Fourthly, off-peak operation during the low-temperature phase results in increased total energy use compared to continuous operation. Lastly, supplemental solar heat in the low-temperature phase lowers the final moisture content of the grain and somewhat reduces the energy requirements per unit of water removed compared to ambient air drying.

A diminishing supply of petroleum fuels and increased competition for petroleum products have made the conservation of energy in grain drying an important cost and management factor. Research on solar grain drying is directed towards utilization of a renewable energy source as an alternative to petroleum fuels for drying. The success of this research would be profitable to small scale farmers of the developing countries as the cost of grain drying operation could thus be reduced. Converse, Foster, and Sauer (1978), working on low-temperature grain drying with solar heat, found that in-bin grain drying systems with solar heat reduced electrical energy required to dry wet harvested sorghum and shelled corn. Drying rate was mostly dependent on airflow rate. Solar heat was more effective during cold and wet weather conditions. All of the solar heat tests demonstrated a faster drying rate when compared to the natural air tests. Grain deterioration was confined to the upper grain layers.

4. Proposed Dryer for Developing Countries

The use of advanced technology in grain drying, storage and processing has made it possible for farmers in developed countries throughout the world to farm large acreages, thus increasing their production to the extent that they have a surplus to sell or give to developing countries. In developed countries, it is not spectacular to find many centralized drying and processing plants. Not only are these plants easy to purchase, but the farmers are educated enough to operate and maintain them. The cost of importing a continuous dryer, even a batch dryer, to a country in, say, Africa, is so high that the peasant farmers in such a country would not be able to afford it. At the government level, some developing countries have received aid from some developed countries in the form of silos, dryers, and barn machinery in addition to a few others purchased by them. These were distributed to the farmers. It was soon realized that to have this equipment was as important as to be able to maintain, repair, and operate it. As mentioned earlier, the farmers were not able to keep this equipment going due to lack of finance and knowledge. Also road networks are not good enough to reach every farmer producing grain, and such farmers could not have these modern drying and processing facilities. Invariably, these farmers are limited to 5-10 acre plots from which they can cultivate about 5 acres for grain and use the balance for other purposes. Such a farmer could realize about 10,000 pounds of grain from which he would feed his family and sell the balance. It is this balance that causes him the greatest headache. If he delays selling the grain, he may lose the whole produce if he cannot store it at the correct moisture content. Since a farmer can always collect more money for his grain if he delays selling till the time the produce is scarce in the market, it will pay him to dry this produce well enough for adequate storage. He now wants someone to introduce to him a low cost dryer which he can possibly build himself and maintain with little cost, yet which can give uniform drying without requiring mechanical power. It is observed that unless drying operations are undertaken at the level of the farmers, the problem of high moisture content cannot be tackled to prevent deterioration of quality in food grains.

Some research work has been carried out in an effort to develop a simple low cost grain dryer for use by small scale farmers in developing countries.

In the Philippines, the bush dryer called Kukum dryer was developed. This is also known as the Samoa Dryer in Colombia. In Colombia it was used for drying cocoa beans. The source of fuel for this type of dryer could be wood, coal, coconut shell or palm kernel shells.

In the Philippines, four 44-gallon oil drums were used as the heat exchanger. Air temperatures used for drying are often 80°C, dropping to 60°C as the material dries. The floor is covered with gunny sacks to improve heat distribution. The floor is bamboo supported with ½" mesh poultry netting. This dryer has been used for copra nut drying.

Brook (1961) used the specifications and results obtained by Bournville (1958), and modified the specifications in 1961, 1962, and 1963 to dry groundnut in Mokwa, Northern Nigeria. The dryers were based on a simple heat exchanger, using wood fuel, the heated air rising through the drying floor by convection.

Later, Webb (1969) modified Brook's model and tested it for drying maize in the Western state of Nigeria. He raised the plenum chamber height to 2.5 feet to prevent the grain in the center from scorching. He recommended that a four inch layer of shelled maize could successfully be dried with drying air of 130°F. This dryer could dry one metric ton of maize in 72 hours and 1,000 pounds of maize in 24 hours. Thorshaug (1974) stated that it takes 2 to 3 days to dry about 2,200 pounds of unshelled maize from 25 percent to 12 percent with the layer 1 to 1.4 feet thick in a 7.3 feet x 8 feet dryer.

Ryu (1976), in his master's thesis at Kansas State University, further developed the "Brook" dryer for the unskilled farmers in developing countries. In the first phase of the investigation, Ryu evaluated the "Brook" dryer in terms of airflow rate and its relationship with the air inlet size, the grain depth, the temperature rise and the height of the drying floor. The results revealed that the airflow rate increased with the temperature rise and increased drying floor height, but decreased as the grain depth increased. The air inlet size had a significant effect on the airflow rate. The maximum allowable velocity through the air inlet appeared to be 53 ft/min. The following equation, which can be used to predict the airflow rate of the "Brook" drier, was developed:

$$q = .0024\ H\Delta T\ \ D^{-0.76}$$

where

q = the rate of airflow per unit area of bed, cfm/ft^2

H = the height of the drying floor from the centre of the flue in inches

ΔT = the temperature rise from the inlet air temperature to the mean plenum temperature, ^{o}F

D = the grain depth in bed, inches

Wind has a tremendous effect on the airflow rate. The test showed that even a 5 mph wind increased the airflow rate about 5 times over natural convection without wind.

In the second phase of the investigation, Ryu found that the modified air inlet size increased the airflow rate as much as 23 percent over the conventional "Brook" drier. The drying capacity of the "Brook" dryer was increased proportionally by increasing the height of the drying floor without reducing the utilization of heat.

The evaporation rate of the "Brook" dryer with a modified air inlet and 50 percent higher drying floor increased about 50 percent over the unmodified.

The moisture gradient reduced significantly with the increase in height of the drying floor in the modified drier. Mixing or turning the grains five times during drying process from 25 percent to 12 percent eliminated the final moisture gradient between the top and bottom of the bed. There was also some improvement in the drying rate by mixing or turning the bed.

Finally Ryu discovered that increasing the airflow rate by means of a forced draft improved the utilization of heat by decreasing heat loss through the wall. The evaporation rate in forced draft drying with the airflow rate of 15cfm/bu was 0.66 lb water/hr.bu, which is about three times higher than that of the natural convection drying. The temperature difference between the front and back side of the drying floor was reduced considerably by increasing the height of drying floor. Consequently, there was a significant reduction in moisture gradient with the modified dryer.

Bolduc (1978) in his master's thesis at Kansas State University, further modified the "Brook" dryer and compared the performance of the modified one with the unmodified dryer by testing the (i) initial moisture content of 20 percent and 25 percent (w.b.), (ii) grain depths of 4 inches and 6 inches,

(iii) effect of turning the grain every 2 and 4 hours, using no turning as a control and, (iv) air intake of 1/2 and full, on the drying rate, the fuel efficiency and the grain quality (moisture gradient).

The modifications made on the unmodified dryer were as follows: (1) the floor height was increased from 3'4" to 5'5" above the flue; (2) the air inlet was increased from 3.65 $feet^2$ to 8.65 $feet^2$; (3) the flue trench was wedged from the air inlet back to the chimney end.

Bolduc (1978) found that the effect of turning the grain and the air inlet size gave significant improvement on the drying performance of the dryer. Increasing the height of the drying floor showed a more equitable distribution of temperature throughout the bed. Finally, he found that fuel efficiency was better in the modified dryer than in the unmodified one, thereby reducing the cost of operation.

It is intended to further improve the "Brook" dryer to give a better drying performance without raising the cost of construction appreciably beyond the financial capability of the small scale farmers in developing countries.

OBJECTIVES

The broad objective of this study is to develop a more efficient, simple, low-cost grain dryer which can be used at farm and village levels in developing countries.

Specific objective

To evaluate the drying performance of a modified low-cost natural air convection dryer using two pyramidal covers of different heights. A modified Brook's dryer is to be used. In carrying out this objective, experiments were designed to look at three main factors on the drying time, rate of drying, fuel consumption and thermal efficiency of the dryer. The three main factors are:

a. Initial moisture content (25% moisture content and 20% moisture content)

b. Heights of pyramidal cover (no-cover, 3' cover and 5' cover).

c. Effect of turning the grain (4-hr turning and 6-hr turning).

MATERIALS AND METHODS

The intention of this study is to further improve the conventional Peace Corps-Benin-Brook Natural air convection dryer which was evaluated by Bolduc (1978).

In this study, therefore, the modified dryer used by Bolduc (1978) was further improved by designing a pyramidal cover of two different heights and placing these in turn over the floor of the dryer. Series of experiments were then performed to evaluate the effect of these covers, initial moisture content and turning rates on the performance of the dryer and then comparing the results with those obtained with no cover on the dryer.

The detailed construction procedures of the dryer used are given in Bolduc (1978). The material to be dried, shelled corn, is placed on a removable perforated metal sheet (as shown in Figure 1) and mounted over a plenum chamber. The walls enclosing the plenum chamber were constructed of adobe and have a cross-sectional area of 100 $feet^2$. The grain was put on the perforated steel sheet secured on ten 4" x 4" x 8' cedar beams (Figure 1) and was attached to the walls with adobe.

The heating unit consists of three 55 gallon oil drums with all the ends cut out in the manner explained in the "Procedure for Construction of Modified Dryer" given in Bolduc (1978). These drums were placed inside the enclosed plenum chamber as seen in Figure 2. Air is let into the plenum chamber through the two air entrances on either side of the first 55 gallon oil drum (Figure 3). The air inlets are of the same dimension. The adobe walls are 1' thick where they enclose the stoking-pit hole on the sides. The function of the adobe wall is to protect the pit against water flow. The detailed dimensions of the dryer used are given in Table 1.

Table 1. Dimensions of the Dryer Used

Description	Dimension
Size of drying bed	8' x 8'
Height of drying floor from centre of flue	6' 5"
Diameter of flue	2'
Clearance between the flue-pit wall and the flue cylinder at the centre edge of the flue:	
(Front)	1'
(Rear)	6"
Size of Air inlet	8.65 $feet^2$
Materials of walls	1' thick adobe

The pyramidal cover was constructed with ¼" plywood whose thermal conductivity is 0.06 Btu-ft/hr ^{o}F ft^2 (Agricultural Engineers' Handbook). The first one was 9.0' x 9.0' at the base and 4.5' x 4.5' at the top, and 3' high.

Figure 1. The Modified Brook Dryer Showing a Drying Floor

Figure 2. The Flue and Plenum Chamber of the Dryer

Figure 3. Firebox with Adjusted Draft Cover

The frame work of the pyramid was constructed with 1" x 1" wood, and then covered with the plywood with nails (See Figure 4).

The second one was also 9.0' x 9.0' at the base, but 1.5' x 1.5' at the top and 5' high (See Figure 5).

In order to reduce cost, a small one (4.5' x 4.5' at the base and 1.5' x 1.5' at the top and 2' high) was constructed and placed on top of the first one, instead of constructing a new one as described for the 5' high one above. Angle iron 2" x 2" x 55" was used to keep the corners of the joints secure so that wind might not blow the top one off and to prevent sagging at the points of joint when the heat of the hot air leaving the grain begins to have effect on the plywood.

A small window, 2' x 2', was cut as entrance in the first cover to enable the experimenter to enter into the dryer to lay thermocouples, and to spread, turn, and unload the grain. The window was made airtight so that heat is not lost through it during drying trials.

An overall view of the dryer under the protection shelter and the pyramidal cover is shown in Figure 6.

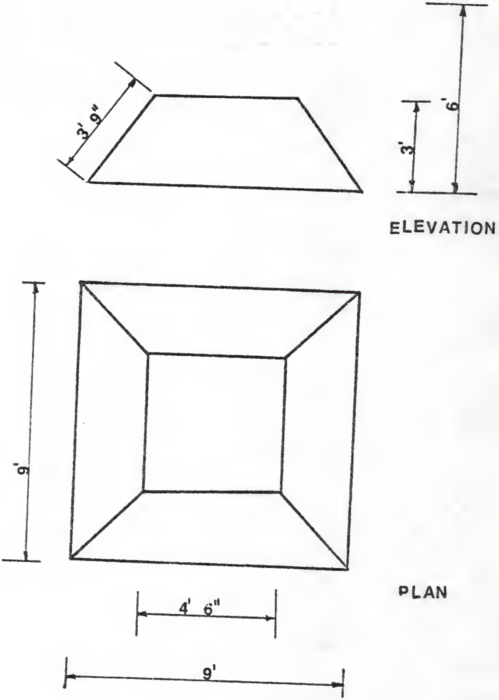


Figure 4. Dimensions of 3' High Pyramidal Covers

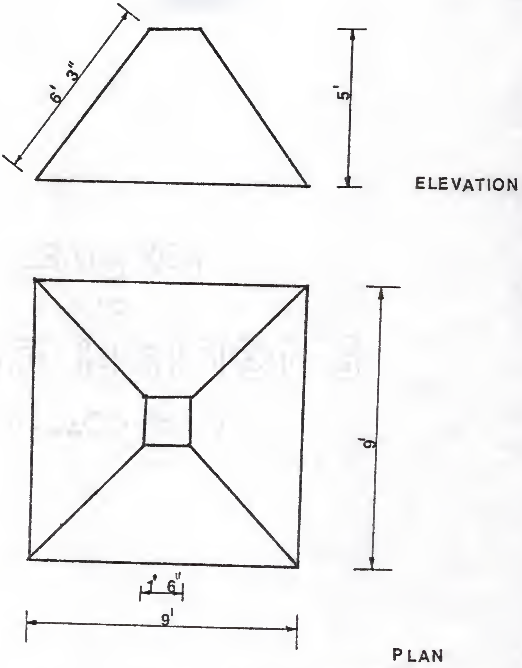


Figure 5. Dimensions of 5' High Pyramidal Cover

Figure 6. An Overall View of the Dryer under the Protection Shelter and the Pyramidal Cover

For the experiments, the inlet air temperature was monitored by using an ordinary centrigrade thermometer. The temperatures of the drying air were measured by thermocouples placed at two fixed locations below the drying floor, i.e., inside the plenum chamber, at the front and back of the drying floor. A full air inlet was used throughout the experiments. Five thermocouples were placed at five locations on the first layer (1-2 kernels thick) of grains to be dried, to measure the temperatures of the bottom layer grain each time readings were taken. Also, five other thermocouples were placed at five locations (1-2 kernels) below the top of the grains to be dried. The thermocouple was placed above the grain to know the temperature of the air finally leaving the grain. Readings were taken at the start of each experiment, then every two hours for the first two to three readings, and thereafter every four or six hours.

The experiments were started towards the end of October 1978, and because farmers had to harvest their maize earlier than usual in 1978 due to weather conditions, it was not possible to use fresh maize from the field. As a result, the grain, which was shelled yellow dent corn, had to be tempered from about 12-13 percent to 20 percent and 25 percent depending on the samples desired. At each experiment for 4" depth of grain, the amount of grain used was 1,000 pounds before drying.

The tempering of corn was carried out by first measuring the initial moisture content of the dried maize. Then the calculated amount of water needed to bring the moisture content of 1,000 lbs of the grain to either 25% or 20% was added.

The grain and water were then sealed up in oil drums and rolled for about 45 minutes, and tempered for three days. At the end of three days, the results were usually nearly accurate with an error of about $\pm 2\%$.

The weight of the wood used for drying at each trial was known and recorded, as well as the ambient air conditions each time a set of readings was taken. The heating value of oak wood used is 7,100 Btu/lb (taken from Brooker et al., 1974). The moisture content of the grain as it progressively dried was measured using the Motomco Moisture Meter each time readings were taken for each trial. About 1,000 grams of samples at various spots at the bottom of the grain depth were usually taken to know the moisture content. This was repeated for the top of the grain depth to know the moisture content at the top of the grain. Turning of the grain was carried out every four and six hours.

Airflow rate was calculated using the equation developed by Ryu (1976) for the "Brook" dryer.

$$q = 0.0024\ H\ T\ D^{-0.76}$$

where

q = the rate of air flow per unit area of bed, cfm/ft^2

H = the height of drying floor from the centre of the flue, inch.

T = the temperature rise from the inlet air temperature to the mean plenum temperature, ^{o}F.

D = the grain depth in bed, inch.

To measure the airflow velocity to the grain, and from the grain, a hot-wire anemometer (model B-22: Hastings-Haydist, Inc.) was used.

Since the moisture content of the top grain was more critical for storage purposes, each trial was stopped when the moisture content of the top grain came down to about 13 percent. For the purpose of analysis, the final cutoff moisture content for all the trials was 13% (w.b.).

The relative humidity of the ambient air was measured by the sling wet and dry bulb thermometer at the initial stage of the experiments. Later, the Precision Hygrometer was used. Heat loss through the dryer walls and the pyramidal cover was excluded in the calculations.

Continuous drying was carried out with grain at 25% (w.b.) initial moisture content and 20% (w.b.) initial moisture content. Continuous drying is drying of two batches of grain (1000 lbs per batch), one after the other without allowing the dryer to cool down after the first dried batch is removed from the dryer before loading the second batch on the dryer. The greater performance of the dryer obtainable in this case depended largely on the speed with which the first batch was removed from the dryer and the second batch loaded on the dryer. There was no mechanical equipment for loading or unloading this type of dryer.

Table 2. Experimental Design

Initial Moisture Content	Cover	Turning	Replication I	Replication II	Continuous
25%	No Cover	4 hour	A1	B1	
		6 hour	A2	B2	
	3ft cover	4 hour	A3	B3	
		6 hour	A4	B4	
	5ft cover	4 hour	A5	B5	C1
		6 hour	A6	B6	
20%	No Cover	4 hour	A7	B7	
		6 hour	A8	B8	
	3ft cover	4 hour	A9	B9	
		6 hour	A10	B10	
	5ft cover	4 hour	A11	B11	C2
		6 hour	A12	B12	

C1 - Continuous drying i.e. drying of second batch (1000 lbs) of grain after the first batch (1000 lbs) had been dried and removed without allowing the dryer to cool down with 25% (w.b.) initial moisture content, 4-hr turning and 5' cover.

C2 - Same as C1 but with 20% (w.b.) initial moisture content instead of 25% (w.b.) initial moisture content.

Table 3. Description of All Drying Tests

TEST NUMBER	DESCRIPTION
D-25-0-1 D-25-0-2	4" grain depth, turning of grain every 4hrs., 25% (w.b.) initial moisture content, no cover, Replications 1 and 2.
E-25-0-1 E-25-0-2	4" grain depth, turning of grain every 6hrs., 25% (w.b.) moisture content, no cover, Replications 1 and 2 .
F-25-3-1 F-25-3-2	4" grain depth, turning of grain every 4hrs., 25% (w.b.) initial moisture content, 3ft high cover, Replications 1 and 2 ,
G-25-3-1 G-25-3-2	4" grain depth, turning of grain every 6hrs., 25% (w.b.) moisture content, 3ft high cover, Replications 1 and 2.
H-25-5-1 H-25-5-2	4" grain depth, turning of grain every 4hrs., 25% (w.b.) initial moisture content, 5ft high cover, Replications 1 and 2.
J-25-5-1 J-25-5-2	4" grain depth, turning of grain every 6 hrs., 25% (w.b.) initial moisture content, 5ft high cover, Replications 1 and 2.
P-20-0-1 P-20-0-2	4" grain depth, turning of grain every 4hrs., 20% (w.b.) initial moisture content, no cover, Replications 1 and 2.
Q-20-0-1 Q-20-0-2	4" grain depth, turning of grain every 6hrs., 20% (w.b.) initial moisture content, no cover, Replications 1 and 2.
R-20-3-1 R-20-3-2	4" grain depth, turning of grain every 4hrs., 20% (w.b.) initial moisture content, 3ft high cover, Replications 1 and 2.

Table 3 (continued)

TEST NUMBER	DESCRIPTION
S-20-3-1 S-20-3-2	4" grain depth, turning of grain every 6hrs., 20% (w.b.) initial moisture content, 5ft high cover, Replications 1 and 2.
T-20-5-1 T-20-5-2	4" grain depth, turning of grain every 4hrs., 20% (w.b.) initial moisture content, 5ft high cover, Replications 1 and 2.
U-20-5-1 U-20-5-2	4" grain depth, turning of grain every 6hrs., 20% (w.b.) initial moisture content, 5ft high cover, Replications 1 and 2.
C-25-5-A	4" grain depth, turning every 4hrs., 25% (w.b.) moisture content, 5ft high cover, continuous drying.
C-20-5-B	4" grain depth, turning of grain every 4hrs., 20% (w.b.) initial moisture content, 5ft high cover, continuous drying.

RESULTS AND DISCUSSION

In this study, a total of 26 experiments were carried out, consideration having been given to two initial moisture contents, 25% (w.b.), and 20% (w.b.) Three different covers (no-cover, 3' cover and 5' cover), were used; the 3' cover and the 5' cover are newly designed modifications to improve the performance of the dryer. In addition, two turnings (4-hr turning and 6-hr turning) were tested to see which one would give greater performance of the dryer. In addition, two turnings (4-hr turning and 6-hr turning) were tested to see which one would give greater performance over the other. For each model (initial moisture content, cover and turning) two replications were carried out as in Table 2. In all the tests, full air inlet was used and the grain depth was 4 inches.

Results were analyzed, in all the 26 experiments, with the final moisture content taken as 13.0% (w.b.).

Table 4 contains the experimental results for all the drying tests carried out. The first column shows the test numbers while the second and third columns give the initial moisture content and final moisture content respectively, in wet basis and dry basis forms. The fourth column shows the weight of water removed from 1000 lbs of shelled yellow corn at each test, measured in pounds weight. The fifth column gives the total time (in hours) taken for each experiment and the sixth column gives the total amount of wood-fuel (in pounds)

Table 4. The Experimental Results for All the Drying Tests

Test No.	M_o		M_f		Weight of Water Removed (lbs)	Drying Time (hrs)	Weight of Wood used (lbs)	Rate of Drying $\left(\frac{\text{lbs } H_2O}{\text{hr}}\right)$	Fuel Consumption $\left(\frac{\text{lbs wood}}{\text{lb } H_2O}\right)$
	% w.b.	% d.b.	% w.b.	% d.b.					
D-25-0-1	24.97	33.28	13.00	14.94	183.4	28.75	195.01	6.38	1.063
D-25-0-2	25.24	33.76	13.00	14.94	188.2	26.75	192.56	7.04	1.023
E-25-0-1	25.40	34.05	13.00	14.94	191.1	25.75	181.18	7.42	0.948
E-25-0-2	24.86	33.08	13.00	14.94	181.4	29.50	196.02	6.15	1.081
F-25-3-1	25.00	33.33	13.00	14.94	183.9	18.75	161.82	9.81	0.880
F-25-3-2	25.18	33.65	13.00	14.94	187.1	14.75	115.38	12.68	0.617
G-25-3-1	24.40	32.28	13.00	14.94	173.4	15.25	143.00	11.37	0.825
G-25-3-2	24.54	32.52	13.00	14.94	175.8	12.75	103.20	13.79	0.587
H-25-5-1	24.43	32.33	13.00	14.94	173.9	13.13	104.08	13.24	0.599
H-25-5-2	25.84	34.84	13.00	14.94	199.0	14.50	134.21	13.72	0.674
J-25-5-1	24.75	32.89	13.00	14.94	179.5	12.75	98.87	14.08	0.551
J-25-5-2	24.11	31.77	13.00	14.94	168.3	12.25	112.65	13.74	0.669

Table 4 (continued)

Test No.	M_o		M_f		Weight of Water Removed (lbs)	Drying Time (hrs)	Weight of Wood used (lbs)	Rate of Drying ($\frac{lbs\ H_2O}{hr}$)	Fuel Consumption ($\frac{lbs\ wood}{lb\ H_2O}$)
	% w.b.	% d.b.	% w.b.	% d.b.					
P-20-0-1	20.45	25.71	13.00	14.94	107.7	22.50	164.65	4.79	1.529
P-20-0-2	20.45	25.71	13.00	14.94	107.7	20.00	156.57	5.39	1.454
Q-20-0-1	20.55	25.87	13.00	14.94	109.3	21.00	137.56	5.20	1.259
Q-20-0-2	19.86	24.78	13.00	14.94	98.4	21.25	144.57	4.63	1.469
R-20-3-1	19.67	24.49	13.00	14.94	95.5	11.50	128.52	8.30	1.346
R-20-3-2	20.34	25.53	13.00	14.94	105.9	13.50	123.26	7.84	1.164
S-20-3-1	20.23	25.36	13.00	14.94	104.2	11.00	94.94	9.47	0.911
S-20-3-2	19.37	24.02	13.00	14.94	90.8	12.00	103.01	7.57	1.134
T-20-5-1	20.80	26.26	13.00	14.94	113.2	8.75	100.58	12.94	0.888
T-20-5-2	20.95	26.50	13.00	14.94	115.6	9.75	105.75	11.86	0.915
U-20-5-1	19.80	24.69	13.00	14.94	97.5	8.50	84.74	11.47	0.869
U-20-5-2	20.02	25.03	13.00	14.94	100.9	8.25	85.01	12.23	0.843
C-25-5-A	24.96	33.26	13.00	14.94	183.2	11.25	97.91	16.28	0.534
C-20-5-B	20.07	25.11	13.00	14.94	101.7	8.50	59.71	11.96	0.587

to heat the air used to remove the moisture given in the fourth column. Column 7 gives the calculated drying rate (lbs water removed per hour) while column 8 gives the calculated fuel consumption (lbs wood per lb water removed).

The graphical representations of typical drying tests showing the effects of turning rate, initial moisture content and cover with respect to the average percentage of moisture content - time relationship are given in Figures 7 and 8. The best results were demonstrated when the dryer was covered with 5' cover.

The typical results for the grain temperature and the plenum air temperature variations during the drying tests at different initial moisture content with three types of cover, and at 6-hour turning are presented in Figures 9 and 10. The temperature curves show some difference in temperature variations among the three types of cover (no-cover, 3' cover and 5' cover) used.

Table 4A presents the temperature rise of the air entering the grain bed after it had been heated at the plenum chamber. The range of this temperature rise was between 35^{O}F and 44^{O}F with an average of 40^{O}F while the average temperature of the cold air was 51^{O}F. It was observed the temperature rise for each test presented in the table was nearly the same. The results are for same tests as in Figures 9 and 10.

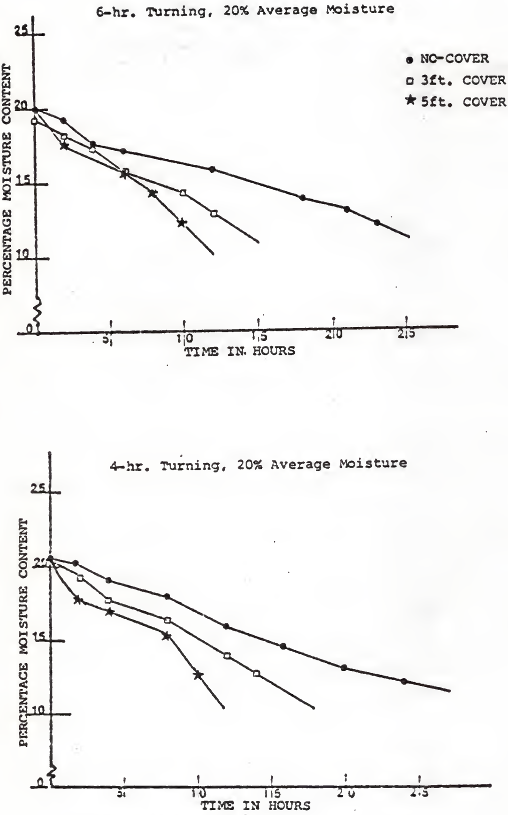
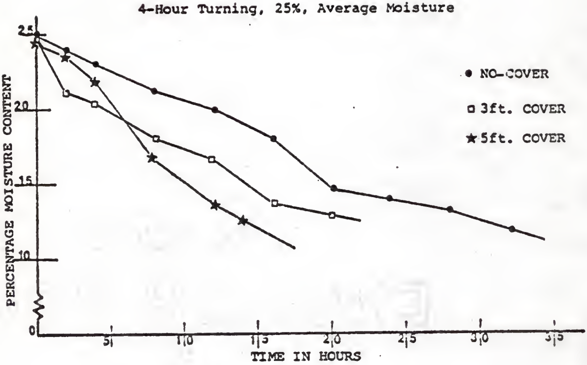


Figure 7. Average Moisture Distribution in Grain Bed



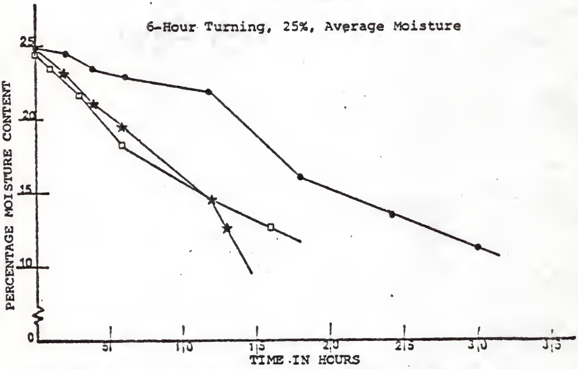


Figure 8. Average Moisture Distribution in Grain Bed

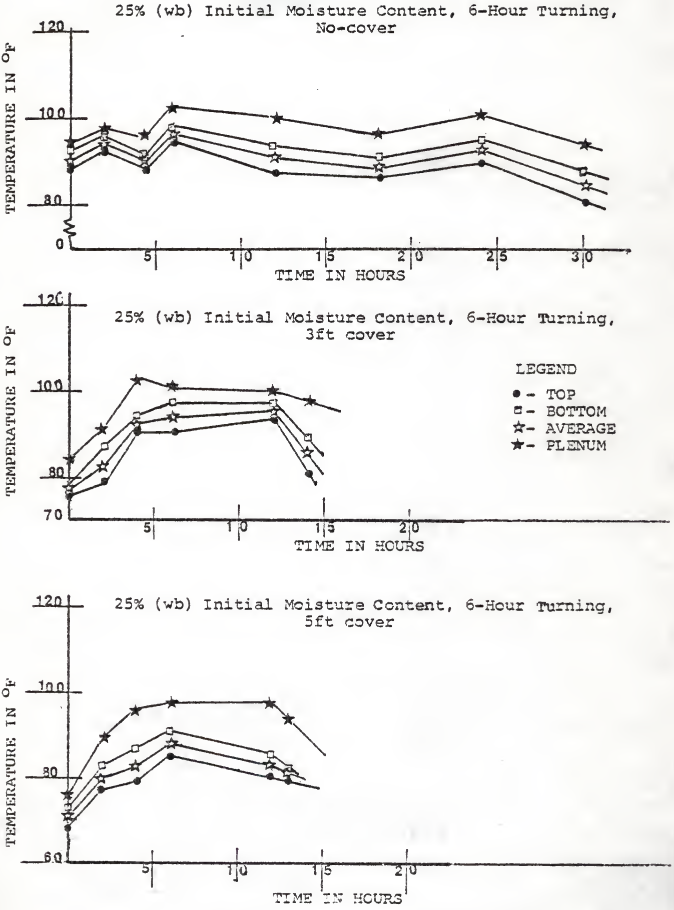


Figure 9. Temperature Variations of Drying Tests

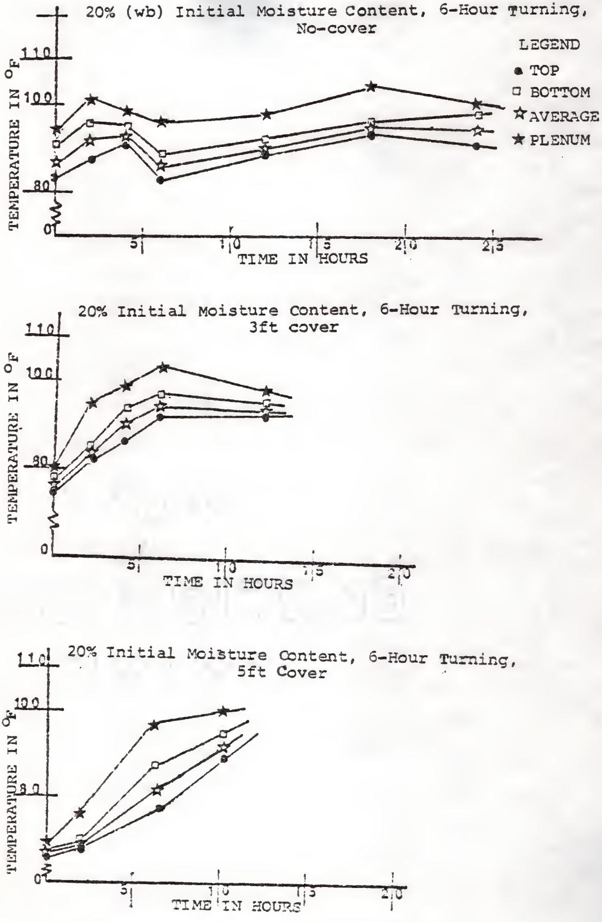


Figure 10. Temperature Variations of Drying Tests

Table 4A. Test Results for Average Air Temperature for Corn Drying Tests

Test No.	Inlet Temp. (°F)	Plenum Temp. (°F)	Leaving Temp. (°F)	Temp. rise (°F)
E-25-0-1	57.3	97.9	83.0	40.6
G-25-3-1	37.9	78.0	47.4	40.1
J-25-5-2	42.3	86.0	67.4	43.7
Q-20-0-1	59.9	99.1	85.6	39.2
S-20-3-1	59.3	94.5	81.8	35.2
U-20-5-2	47.7	88.4	74.2	40.7

Table 5 illustrates the effect of initial moisture content, cover, and turning with respect to drying time, drying rate, fuel consumption and thermal efficiency. In determining thermal efficiency values, the heat of vaporization of water in grain was taken as 1500 Btu/lb (Brooker et al., 1974) and the heat content of the wood used was also taken as 7100 Btu/lb (Brooker et al., 1974). The table also gives percentage increase or decrease using no-cover as control, to show clearly the different effects of initial moisture content, cover and turning on the average of each of the parameters listed above.

Drying grain from 25% (w.b.) to 13% (w.b.) the range of average drying time was from 13 hrs. (minimum) to 28 hrs. (maximum) while that for average drying rate was from 6.71 lbs water/hr (minimum) to 14 lbs water/hr (maximum). Also, the range of average fuel consumption was from 0.610 lbs wood/lb water (minimum) to 1.043 lbs wood/lb water (maximum) while that for average thermal efficiency was from 20% (minimum) to 35% (maximum). Drying grain from 20% (w.b) initial moisture content, to 13% (w.b.), the range of average drying time was from 8 hrs. (minimum) to 21 hrs. (maximum) while that for average drying rate was from 5 lbs water/hr (minimum) to 12 lbs water/hr (maximum). Also, the range of average fuel consumption was from 0.856 lbs wood/lb water (minimum) to 1.492 lbs wood/lb water (maximum) and that for average thermal efficiency was from 19% (minimum) to 65% (maximum). The results revealed differences in the performance of the dryer with respect to the initial moisture content, type of cover and turning. The significance of these differences is analyzed later statistically.

From the table, if we compare covering the dryer with the 3' pyramidal cover against no-cover, the 3' cover gave a reduction of 40% in drying time (16.8 hrs vs 27.8 hrs), a reduction of 28% in fuel consumption (0.749 lbs wood/lb water vs 1.043 lbs wood/lb water), an increase of 68% on drying rate (11.25 lbs water/hr vs 6.7 lbs water/hr) and an increase of 44% on thermal efficiency, (29.14% vs 20.26%) for 25% (w.b.) moisture content and 4-hr turning over those obtained with no cover.

In like manner, the 5' cover gave a reduction of 50% in drying time (14 hrs vs 28 hrs), a reduction of 39% in fuel consumption (0.637 lbs wood/lb water vs 1.043 lbs wood/lb water), an increase of 101% in drying rate (13.48 lbs water/hr vs 6.71 lbs water/hr) and an increase of 65% in thermal efficiency (33% vs 20%), for 25% (w.b.) initial moisture content and 4-hr turning over those obtained with no cover.

For 25% (w.b.) initial moisture content and 6-hr turning, the 5' cover gave a reduction of 55% in drying time (12.5 hrs vs 27.6 hrs), a reduction of 40% in fuel consumption (0.610 lbs wood/lb water vs 1.015 lbs wood/lb water), an increase of 105% drying rate (14.9 lbs water/hr vs 6.8 lbs water/hr), and an increase of 67% in thermal efficiency (35% vs 21%) over those

Table 5. Average Values of the Drying Test Results for Two Replications at Different Test Conditions

Moisture	Turning	Cover	Test No.	Average Drying Time Hrs.	Average Drying Time % Decrease	Average Drying Rate lbs H_2O/hour	Average Drying Rate % Increase	Average Fuel Consumption lbs wood/lb water	Average Fuel Consumption % Decrease	Average Thermal Efficiency %	Average Thermal Efficiency % Increase
25%	4-Hour	No-Cover	D-25-0-1 D-25-0-2	27.75		6.71		1.043		20.26	
		3ft-Cover	F-25-3-1 F-25-3-2	16.75	39.6	11.25	67.7	0.749	28.2	29.14	43.8
		5ft-Cover	H-25-5-1 H-25-5-2	13.82	50.2	13.48	100.9	0.637	38.9	33.32	64.5
	6-Hour	No-Cover	E-25-0-1 E-25-0-2	27.63		6.79		1.015		20.92	
		3ft-Cover	G-25-3-1 G-25-3-2	14.00	49.3	12.58	85.3	0.706	30.4	30.81	47.3
		5ft-Cover	J-25-5-1 J-25-5-2	12.50	54.8	13.91	104.9	0.610	39.9	34.96	67.1

Table 5 (continued)

Moisture	Turning	Cover	Test No.	Average Drying Time Hrs.	Average Drying Time % Decrease	Average Drying Rate $\frac{lbs\ H_2O}{hour}$	Average Drying Rate % Increase	Average Fuel Consumption $\frac{lbs\ wood}{lb\ water}$	Average Fuel Consumption % Decrease	Average Thermal Efficiency %	Average Thermal Efficiency % Increase
20%	4-Hour	No-Cover	P-20-0-1 P-20-0-2	21.25		5.09		1.492		14.18	
		3ft-Cover	R-20-3-1 R-20-3-2	12.50	41.2	8.07	58.5	1.255	15.9	16.93	19.4
		5ft-Cover	T-20-5-1 T-20-5-2	9.25	56.5	12.40	143.6	0.902	39.5	23.44	65.3
	6-Hour	No-Cover	Q-20-0-1 Q-20-0-2	21.13		4.92		1.364		15.59	
		3ft-Cover	S-20-3-1 S-20-3-2	11.50	45.6	8.52	73.2	1.023	25.0	20.91	34.1
		5ft-Cover	U-25-5-1 U-25-5-2	8.38	60.3	11.85	140.9	0.856	37.2	24.70	58.4
25%	4-Hour	5ft-Cover	C-25-5-A	11.25	59.5	16.28	142.6	0.534	48.8	39.62	95.6
20%	4-Hour	5ft-Cover	C-20-5-B	8.50	60.0	11.96	135.0	0.587	60.7	35.98	153.7

obtained with no cover.

Thus again, the performance of the dryer when covered with the 5' cover is best when compared with that using either the 3' cover or no cover.

Next, considering the situations for the 4-hr turning and 6-hr turning, the performance when turnings were carried out every six hours definitely showed a better overall performance over turnings every four hours.

When the initial moisture content was 20%, the performance of the dryer, when covered with the 3' cover and 5' cover and compared with the performance when there was no cover on it, is as follows: at 4-hr turning the 3' cover gave a reduction of 41% in drying time (12.5 hrs vs 21.3 hrs), a reduction of 16% in fuel consumption (1.255 lbs wood/lb water vs 1.492 lbs wood/lb water), an increase of 59% in drying rate (8.1 lbs water/hr vs 5.1 lbs water/hr), and an increase of 19% in thermal efficiency (16.9% vs 14.2%) over those obtained with no cover. At the same initial moisture content and turning rate, the 5' cover gave a reduction of 57% in drying time (9 hrs vs 21 hrs), a reduction of 40% in fuel consumption (0.902 lbs wood/lb water vs 1.492 lbs wood/lb water), an increase of 144% in drying rate (12.4 lbs water/hr vs 5.1 lbs water/hr) and an increase of 65% in thermal efficiency (23% vs 14%) over those obtained with no cover. Thus the results have shown that at 20% initial moisture content and 4-hr turning, the performance was best with the 5' cover and the performance when the 3' cover was used was better than when there was no cover at all.

Next the case with 20% initial moisture content and 6-hr turning was considered. The 3' cover gave a reduction of 46% in drying time (11.5 hrs vs 21.1 hrs), a reduction of 25% in fuel consumption (1.023 lbs wood/lb water vs 1.364 lbs wood/lb water), an increase of 73% in drying rate (8.5 lbs water/hr vs 4.9 lbs water/hr) and an increase of 34% in thermal efficiency (20.9% vs 15.6%) over those obtained with no cover.

For the same initial moisture content and 6-hr turning, the 5' cover gave a reduction of 60% in drying time (8.4 hrs vs 21.1 hrs), a reduction of 37% in fuel consumption (0.856 lbs wood/lb water vs 1.364 lbs wood/lb water), an increase of 141% in drying rate (11.85 lbs water/hr vs 4.92 lbs water/hr) and an increase of 58% in thermal efficiency (24.7% vs 15.6%) over those obtained with no cover. Thus, the performance of the dryer is best when covered with the 5' cover viewing the effects of the three types of cover.

When the 6-hr turning was compared with the 4-hr turning, the dryer performance in general appeared to be better at the 6-hr turning than at the 4-hr turning.

In comparing the performance of the dryer when the initial moisture content was 25% (w.b.) with that when the initial moisture content was 20% (w.b.), it was observed that the effect of moisture on the dryer performance was more pronounced for 20% (w.b.) initial moisture content. Later the effect of initial moisture content on the performance of the dryer was tested statistically to know its significance.

In conclusion the results have shown that if the dryer has a 5' cover and the turning is carried out every six hours, a better dryer performance can be obtained whether the initial moisture content of the grain is at 25% (w.b.) or 20% (w.b.).

The effect of continuous drying was tested as a matter of curiosity. This was the drying of two batches of grain (1,000 lbs per batch) continuously, i.e., drying the second batch without letting the dryer cool down after drying the first batch. Two trials were carried out, one at initial moisture content of 25% (w.b.) with 5' cover and 4-hr turning. The other trial was for 20% (w.b.) initial moisture content, 4-hr turning and 5' cover. The comparisons were made with respect to thermal efficiency. From Table 5, at initial moisture content of 25% (w.b.) and 4-hr turning the continuous drying showed an increase of 96% in thermal efficiency (39.62% vs 20.26%) over that obtained with no cover. Also, at initial moisture content of 20% (w.b.) and 4-hr turning the continuous drying showed an increase of 154% in the thermal efficiency (35.98% vs 14.18%) over that obtained with no cover.

These results show that a better dryer performance can be further obtained if the dryer can be put to work continuously until the harvest has been completely dried.

Table 6 contains results for the airflow rates calculated using the equation developed by Ryu (1976). The average airflow rate (in cubic feet per minute per bushel) for no cover and 25% (w.b.) initial moisture content is 6.30 cfm/bushel, while that for 3' cover is 6.80 cfm/bushel, an increase of 7.9% and that for 5' cover is 8.24 cfm/bushel, an increase of 30.8%. Thus the results show that the airflow rate is best when the dryer is covered with the 5' cover. The same trend is the case with 20% (w.b.) initial moisture content. At no-cover, the average airflow rate is 6.40 cfm/bushel while that for 3' cover is 7.30 cfm/bushel, an increase of 14.1%, and that for 5' cover is 9.50 cfm/bushel, an increase of 48.4%. In this case, turning has no influence at all on airflow rate.

The above results again confirm that the performance of the dryer is best when it is covered with the 5' high pyramidal cover whether the initial moisture content of the grain is 25% (w.b.) or 20% (w.b.).

These results also confirm Ryu's (1976) findings that increasing the airflow rate improved the utilization of heat, especially in the light of the results obtained for thermal efficiency of the dryer. The effect of increasing the airflow rate caused an increase in the thermal efficiency of the dryer.

The SAS program was used for the analysis of variance in examining the effect of initial moisture content, turning and

Table 6. Determination of Airflow Rate, Q cfm/bushel and Percentage Increase over No-cover Values using Ryu's Equation

$$q\frac{(cfm)}{(ft^2)} = 0.0024\ H\Delta TD^{-0.76}$$

$$H = 77ins., \quad D = 4ins.$$

Test No.	Temp. of Air	Temp. of Plenum	ΔT	$Q\ \frac{cfm}{bushel}$	Average $Q\ \frac{cfm}{bushel}$	% Increase
D-25-0-1	80.33	99.90	19.57	4.71		
D-25-0-2	74.65	97.70	23.05	5.54	6.30	
E-25-0-1	57.30	97.90	40.60	9.76		
E-25-0-2	71.94	94.10	22.16	5.33		
F-25-3-1	44.40	62.00	17.60	4.23		
F-25-3-2	65.60	96.50	30.90	7.43	6.80	7.9
G-25-3-1	37.90	78.00	40.10	9.64		
G-25-3-2	71.45	96.00	24.55	5.90		
H-25-5-1	65.28	88.30	23.02	5.54		
H-25-5-2	49.46	87.70	38.24	9.20		

Table 6 (continued)

Test No.	Temp. of Air	Temp of Plenum	ΔT	Q $\frac{cfm}{bushel}$	Average Q $\frac{cfm}{bushel}$	% Increase
J-25-5-1	59.60	91.60	32.00	7.70	8.24	30.8
J-25-5-2	42.30	86.00	43.70	10.51		
P-20-0-1	77.20	99.10	21.90	5.27	6.40	
P-20-0-2	73.63	97.70	24.07	5.79		
Q-20-0-1	59.90	99.10	39.20	9.43		
Q-20-0-2	74.19	95.60	21.41	5.15		
R-20-3-1	57.92	89.60	31.68	7.62	7.30	14.1
R-20-3-2	62.45	94.60	32.15	7.73		
S-20-3-1	59.30	94.50	35.20	8.46		
S-20-3-2	72.95	96.10	23.15	5.57		
T-20-5-1	19.63	73.40	53.77	12.93	9.5	48.4
T-20-5-2	50.00	82.40	32.40	7.79		
U-20-5-1	52.70	84.00	31.30	7.53		
U-20-5-2	47.7	88.40	40.70	9.78		
C-25-5-A	54.95	94.90	39.95	9.61	9.61	52.5
C-20-5-B	59.62	97.80	38.18	9.18	9.18	43.4

cover on drying rate, thermal efficiency and fuel-consumption. The results of analyses are given in Tables 7, 8 and 9.

From the ANOVA tables, the cover and initial moisture content show significant effect on the performance of the dryer; however, turning, the interaction between cover and turning, the interaction between cover and moisture, the interaction between cover, turning and moisture, and the interaction between moisture and turning all have no significant effect on the performance of the dryer. This test was performed with 95% confidence and hence the level of significance, α, was taken as 0.05.

On the whole, these statistical analyses have certainly confirmed earlier observations and conclusions that the best performance of the dryer in this study was obtained with the sample at 25% (w.b.) initial moisture content, 6-hr turning and with the dryer covered with the 5' high cover. Although the statistical test showed non-significant effect of the turning rate (4 hours vs 6 hours), a close examination of the data showed consistently higher performance of the dryer with 6-hour turning than with 4-hour turning. Nevertheless, there is a definite advantage with respect to reduction in the labor cost of operation when turning is performed at every six hours rather than at every four hours.

The next statistical analysis performed on the results obtained in this study was to find an equation that would best

Table 7. Analysis of Variance For Drying Rate

Source	Degree of Freedom	Sum of Squares	F-Value
Initial moisture content	1	32.0397	33.82*
Cover	2	200.6629	105.90*
Turning	1	0.4082	0.43
Moisture vs. cover	2	5.1527	2.72
Moisture vs. turn	1	0.7455	0.79
Cover vs. turn	2	1.1971	0.63
Moisture vs. cover vs. turn	2	0.1575	0.08

*level of significance, $\alpha = 0.05$

Table 8. Analysis of Variance for Thermal Efficiency

Source	Degree of Freedom	Sum of Squares	F-Value
Moisture content	1	480.0782	36.35*
Cover	2	522.4836	19.78*
Turning	1	18.7974	1.42
Moisture vs. cover	2	32.4095	1.23
Moisture vs. turn	1	1.197	0.09
Cover vs. turn	2	3.5155	0.13
Moisture vs. cover vs. turn	2	1.8301	0.07

*Level of significance, α = 0.05

Table 9. Analysis of Variance for Fuel Consumption

Source	Degree of Freedom	Sum of Squares	F-Value
Initial moisture content	1	0.756	61.01*
Cover	2	0.9283	37.41*
Turn	1	0.0423	3.41
Moisture vs. cover	2	0.0299	1.21
Moisture vs. turn	1	0.0159	1.28
Cover vs. turn	2	0.0105	0.42
Moisture vs. cover vs. turn	2	0.0074	0.30

*Level of significance, $\alpha = 0.05$

fit and adequately describe the moisture-time relationship.

In order to find this equation, regression analysis was performed on the results obtained for 25% (w.b.) and 20% (w.b.) initial moisture, 6-hour turning and the three types of cover, with respect to moisture reduction from initial moisture content to the final moisture content against the time taken. Six sets of data were then used. The form of the equation which best fitted the drying curve was:

$$M = A + BX + CX^2$$

where M = moisture content in %

X = time in hours

A, B, and C are constants

The results of the regression analysis are presented in Table 10.

Table 10. Regression analysis of drying tests $M = A + BX + CX^2$

Test No.	Constant A	Constant B	Constant C	Standard Error of Estimate Y	R^2
1. J-25-5-1	24.706	-0.850	-0.00367	0.3611	0.9957
2. G-25-3-1	24.528	-1.120	+0.02334	0.2826	0.9952
3. E-25-0-1	25.380	-0.420	-0.00217	0.6932	0.9758
4. U-20-5-1	19.690	-1.018	+0.02424	0.2751	0.9972
5. S-20-3-1	20.097	-1.116	+0.03560	0.3026	0.9968
6. Q-20-0-1	20.125	-0.297	-0.00244	0.2941	0.9898

CONCLUSIONS

The following conclusions were made from the results obtained from this investigation.

1. The effect of the pyramidal cover on the dryer performance was significant especially with the 5' cover.
2. The airflow rate increased by 30.8% with the 5' covered dryer over the uncovered dryer at 25% (w.b.) initial moisture content (8.24 cfm/bu vs 6.3 cfm/bu).
3. Initial moisture content affected the performance of the dryer as well, though to a lesser degree than was the case with the pyramidal cover.
4. Statistically, turning had no significant effect on the dryer performance but the 6-hour turning was preferred to the 4-hour turning because the labor cost would be reduced.
5. The thermal efficiency of the dryer with the 5' cover and 6-hour turning increased by 67% over that obtained when the dryer was not covered (35% efficiency vs 21% efficiency).
6. The average fuel consumption reduced by 40% when the dryer was covered with the 5' high pyramidal cover at 6-hour turning when compared with the result obtained when the dryer had no cover with the same turning rate (0.610 lbs wood/lb water vs 1.015 lbs wood/lb water). Also the average drying time reduced by 55% for the same conditions (12.5 hours vs 27.6 hours).
7. With respect to fuel consumption and thermal efficiency

especially, the performance of the dryer improved considerable by continuously drying a second batch immediately after the first batch had been dried and emptied from the dryer. The dryer thermal efficiency increased by 96% for continuous drying at 25% (w.b.) initial moisture content and 5' cover (39.62% vs 20.26%), and by 154% for continuous drying at 20% (w.b.) initial moisture content and 5' cover, over the uncovered dryer (35.98% vs 14.18%). Also the dryer fuel consumption reduced by 49% for continuous drying at 25% (w.b.) initial moisture content and 5' cover (0.534 lbs wood/lb water), and by 61% for continuous drying at 20% (w.b.) initial moisture content and 5' cover, over the uncovered dryer (0.587 lbs wood/lb water vs 1.492 lbs wood/lb water).

8. It is therefore, recommended that for high efficiency, the dryer should be covered with a 5' high pyramidal cover and turning should be carried out at six hour intervals. The initial moisture content could be either 25% (w.b.) or 20% (w.b.). Furthermore, each batch of grain should be dried continuously.

9. From the regression analysis performed, the drying curve for yellow dent maize using the natural convection dryer with modifications recommended above can be described by

$$M = A + BX + CX^2$$

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APPENDIX

Appendix

CONSTRUCTION OF PYRAMIDAL COVER

The materials used are:

¼" thick plywood

1" x 1" white wood

2" x 2" Angle iron

Nails

¼" bolts and nuts

The framework of the cover was first constructed using the 1" x 1" white wood. The base of the frame was made 9ft x 9ft square. It would be recalled the thickness of the adobe wall surrounding the dryer floor was made 1' thick and the dimension of the dryer floor was 8' x 8' square. The dimension of the base was therefore, made to enable the cover sit in the middle of the adobe thickness. At each corner of the base was fixed 3' 9" long (1" x 1") wood at an angle of about 35.12° with the edges of the wood forming the corners of the framework. The height of this corner white wood for the 5ft high cover was 6' 3". To hold these corner woods in position, the other ends were fixed to 4' 6" x 4' 6" square frame.

Next, the sides of this framework were then covered with the ¼" thick plywood.

Another method tried was to fix the plywood cover to the base frame first before strengthening the edges of the cover by nailing the 1" x 1" wood cut to desired lengths to the inner edges of the plywood cover. In order to save some money, a small cover with 4' 6" x 4' 6" square base and 2' high was constructed and placed on top of the 3' high cover to make a 5' high cover. The joints were made air-tight and firm by fixing four No. 2" x 2" x 55" angle iron round them. Strong cloth tape was also used to make doubly sure, the joints were airtight.

WINDOW: A 2' x 2' square window was cut on one side of the cover to enable easy readings of temperatures, collecting samples of grains at scheduled times for measurements and for loading and unloading the dryer. This 2' x 2' piece was fixed to a 2' 6" x 2' 6" square plywood. Then 1" thick white wood constructed into a 2' x 2' frame was also fixed to the sides of this piece, to make the window air-tight though removable each time it was desired to do so.

DEVELOPMENT OF A NATURAL CONVECTION DRYER
FOR USE IN DEVELOPING COUNTRIES

by

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The objective of this study is to further modify the Natural Convention Dryer for an improved performance for use in developing countries. The modifications introduced were pyramidal covers of two different heights. The modifications were expected to increase the performance of the dryer by utilizing more heat from the hot air used in drying the grain material. The grain used in these investigations was yellow dent corn.

The dryer was built of adobe made from Kaolinite clay. A flue and stoking pit trench were first dug as a foundation before the adobe walls were mounted. The flue for the dryer consists of three 55 gallon oil drums laid end to end in the flue trench. The drying floor consist of ten 4" x 4" x 8' cedar logs laid horizontally between the adobe walls to support the perforated metal floor. The fuel used was wood.

The main factors tested on the drying performance of the modified dryer were: 1) Initial moisture contents at 25% (w.b.) and 20% (w.b.); 2) Covers on the dryer (5' high pyramidal cover, 3' high cover and no cover); and 3) Turning rate of the grain (every four hours and six hours).

The parameters used to analyze the results obtained were: drying time (hours), rate of drying (lbs. of water removed per hour), fuel consumption (lbs. of wood used per lb. of water removed), and thermal efficiency of the dryer (in percentage).

Statistical analysis showed that both the effect of cover and initial moisture content were significant on the performance of the dryer. The effect of turning rate of the grain showed no significance on the performance of the dryer. However, turning the grain especially every six hours assisted in reducing the drying time and gave an improved uniform drying. An increased airflow rate was obtained with the 5' cover on the dryer and at 6-hr turning rate. The result obtained with this condition gave an increase of 35% over that obtained when the dryer was not covered (8.24 cfm/bu vs 6.3 cfm/bu).

Among the test models examined, the best dryer performance was obtained with a 5' cover and 6-hr turning period. Comparing the modified Brook dryer under the above condition with the modified dryer without a cover, the following results were obtained: 1. a reduction of 55% in drying time (12.5 hrs. vs 27.6 hrs); 2. a reduction of 40% in fuel consumption (0.610 lbs wood/lb water vs 1.015 lbs wood/lb water); 3. an increase of 105% in drying rate (13.90 lbs/hr vs 6.8 lbs water/hr) and 4. an increase of 67% in thermal efficiency of the dryer (35% vs 21%).

The dryer thermal efficiency increased by 96% for continuous drying at 25% (w.b.) initial moisture content and 5' cover and by 154% for continuous drying at 20% (w.b.) initial moisture content and 5' cover, over the uncovered dryer.

The form of equation which best fits the drying curve is:

$$M = A + BX + CX^2$$

where M = percentage moisture content of grain

X = time in hours

A, B and C = constants

It is therefore recommended that for high efficiency, the dryer should be covered with a 5' high pyramidal cover and turning should be carried out at six hour intervals. The initial moisture content could be either 25% (w.b.) or 20% (w.b.). Furthermore, each batch of grain should be dried continuously.