SOLAR GRAIN DRIER FOR SMALL FARMS IN NORTHEASTERN BRAZIL

by

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ABSTRACT

A crop drier using solar energy to heat ambient air was designed for use in Northeast Brazil. The drier uses no commercial forms of energy. Air is heated about 30°C by a solar panel, passes through a drying chamber, and out through a vertical chimney. Air flow is generated by buoyant forces resulting from the temperature differential.

The solar drier will permit earlier harvesting of grain, thus reducing substantial field losses caused by birds, animals, and insects. It will also improve its storage capabilities. As a result the drier, when fully developed, could help overcome the 20 per cent deficit in the grain supply predicted to occur in Northeast Brazil before the end of the 1980 decade.

Further studies should be conducted to increase air flow and improve distribution.

INTRODUCTION

Scientists who have been studying the food problems around the world point out that improved storage of food grains will contribute toward the solution of world hunger if it receives world-wide attention, particularly in less developed countries. The developing nations in the tropics and subtropics have a population of more than two billion, and it is increasing annually. This creates an increased demand for food grains, and more attention must be devoted to the conditions, facilities, and storage methods in order to preserve the grains and reduce losses and storage costs to a minimum.

Northeast Brazil with almost 27 million people is one area which must develop ways to improve production and storage of food grains. A shortage in grain production of about 20 per cent is expected to occur in that region by the end of the 1980 decade. To prevent field losses, grain must be harvested early when its moisture content is too high for safe storage. In view of this, a design of a solar energy dryer for grains is presented in an attempt to improve the storage efficiency in the region.

The dryer is designed for use in northeast Brazil. Design criteria include consideration of economy, the type of material available in the region, and the absence of any forms of usable energy other than solar. Its use must also require minimum training for the laborers. This study includes initial testing of the design concept under Arizona conditions. Additional studies will be necessary in Brazil to develop a solar dryer which is effective in the somewhat different climate conditions of northeast Brazil.

Statement of the Problem

Description of Situation

Northeast Brazil is located in a tropical region. It includes nine states of the Union, and has about 19 per cent of Brazil's overall area with about 1,550,000 km^2. Population of about 26,675,000 constitutes 30 per cent of Brazil's total, representing the second largest regional population in the country (15).

The region is characterized by its semi-arid climate especially in a large area called "sertao." Periodic droughts have affected its agricultural production. It has two alternating well-defined seasons; the rainy season which occurs from January to May, and dry season for the rest of the year.

Temperatures in the Northeast are usually high with little variation from year to year, season to season, or from day to day. For most of the year the region experiences a temperature range of about 21°C to 35°C with relative humidity ranging from about 55 to 95 per cent.

The difference between the greatest and least monthly mean temperature values ranges from 5° to 10° and that for daily values from 8° to 11° (6).

According to 1970 census data (21), the northeast region has the highest number of farms (2,199,539) followed by the south region (1,274,498). The farms are small and with low productivity, principally because of low soil fertility.

Table 1, from 1970 census data (21), shows that about 68 per cent of the farms had less than 10 ha and represent only 5.5 per cent of the total farm area in the region. The next category, properties of 10 ha to 100 ha constitute 25.53 per cent of the total number and 24.24 per cent of the total area. Farms of 100 ha to 1000 ha comprise only 5.73 per cent of the total number but include 43.43 per cent of the total area. Only 0.39 per cent of the farms are greater than 1000 ha, covering 26.78 per cent of the total area.

The small farms play an important role in agricultural production in Northeast Brazil. A study made by Patrick (16) states that small farms are used primarily for crops rather than livestock.

Data from the 1949 and 1960 census (21) show an increase of 33.10 per cent in the area of land in farms with less than 10 ha, while area in farms with more than 1000 ha increased less than 2 per cent. For the period from 1960

Table 1. Number and area of farms and respective percentages of the total for Northeast Brazil.

Farm Category (ha)	Number of Farms	Percentage of Farms	Category Area (ha)	Percentage of Area
10	1,503,280	68.35	4,090,055	5.54
10-100	561,567	25.53	17,893,871	24.24
100-1000	125,995	5.73	32,059,496	43.43
1000	8,697	.39	19,767,872	26.78

to 1970, hectarage on farms below 100 ha increased less than 3 per cent and farms over 1000 ha increased less than 1 per cent. During the same decade, farms from 100 to 1000 hectares decreased 4.4 per cent.

Patrick also stated that the increase in agricultural production was proportional to the increase in area rather than an increase in unit productivity. The 1960 census shows that the small farms were responsible for an increase of one-third of the total increase in agricultural production in the region.

A group of technicians from the Bank of the Northeast, in an analysis of the agricultural development of the region presented during the IX meeting of the Brazilian Society of Rural Economists, made a projected estimate of the demand for agricultural production in the region for the period between 1970 and 1980 (17). This study indicates that by 1980 there will be a production deficit for most grains produced in the region. In the case of corn the deficit is forecast at 777,000 metric tons. The deficit will have to be compensated by imports or by changes in corn production technology in the Northeast.

Table 2 shows the estimated demand, indicating that corn must be increased by 777,000 metric tons, rice by 534,000 metric tons, and beans by 42,000 metric tons by 1980. This represents a deficit of 26, 8, and 27 per cent for corn, rice, and beans, respectively.

Table 2. Demand and production of the principal agriculture products in Northeast Brazil in 1980.

Products	Total demand (Million tons)	Total demand Annual growth rate 1970-1980 (%)	Estimated production 1980 (million tons)	Deficit or surplus (1,000 tons)
Sugar Cane	39.3	5.1	36.4	-3,009
Manioc	14.2	3.6	14.7	+456
Cotton	2.0	9.9	1.2	-775
Cacao	0.2	3.2	0.2	--
Bean	1.2	2.7	1.1	-42
Corn	3.1	5.2	2.3	-777
Rice	2.2	3.6	1.6	-534

Agricultural productivity studies for the northeast are scarce. With few exceptions, the crop production methods are very primitive. Grains, namely beans, rice, and corn are important food crops grown in that region and are in high demand throughout the year for both human and livestock consumption.

The bulk of grain produced in the region is stored on the farm before it is processed, marketed, consumed, or used for seed. The farmer employs traditional methods for storage common in his area based on local resources and customs.

The farmer attempts to store the grain in as dry a condition as possible. The drying is usually achieved by delaying harvest for two or three or more months, or by harvesting and leaving the grains in an open area exposed to the sun. Some use a combination of methods, delaying harvest for a few weeks and then leaving it in an open area exposed to the sun where the drying is completed.

The harvesting time for the crops usually coincides with the beginning of the dry season. Corn is sometimes left on the stalk and harvested over a long period of time as it is needed. If this is done, the farmer will bend the ear of corn so it hangs upside down on the stalk with the husks still remaining, protecting it from the occasional rains that occur even during the dry season. If it is harvested all at once, it will be placed either shelled or in the ear, exposed to the sun in an open area to be dried naturally before it is stored.

The harvesting of beans follows almost the same process as corn. However, the legume can not be left in the field as long because the pods open spontaneously and shell out when dry. The legumes are usually harvested and placed on an open area exposed to the sun to dry sufficiently for easy shelling. The shelled beans are again place in an open area, also exposed to the sun, for drying to a condition suitable for storage.

Rice plants are left in the field for a period of time, sometimes referred to as the "curing" period, to facilitate the removal of rice grains from the heads. Shelling is accomplished by hand and the grain is exposed to the sun for further drying before storage.

Traditional structures of various forms are available for the storage of cereal grains by farmers. The structures include bins, cribs, granaries, and sheds.

On small farms with production for home consumption only, storage of grains in sacks begins immediately after the crops has been dried by one of the methods mentioned. After the grain has been sacked it is stacked in a shed or within the farmer's house. Sometimes the grain is sacked on the farm and immediately transported to the warehouse by a trader.

Metal containers or small bins are also used by some producers. The capacity of the containers varies from 10 kg to 1000 kg. The metal must be painted to protect it against corrosion common in the region due to climatic conditions. The containers are sealed with beeswax to eliminate as much of the air as possible. The airtight bins are placed within the farmer's house or building for storage. Bulk storage is often used to avoid the cost of sacks or metal containers and labor. The loose grain is placed on the floor safe from rain until it is sold or consumed.

Only a few producers make use of insect control methods during storage. Chemical methods, primarily contact insecticides, respiratory poisons, or fumigants are the only methods practiced. The treatment used for insect control must be safe, low in cost, easily applied, and one that does not require any special equipment.

Grain storage buildings are usually general purpose buildings containing sacks, metal bins, bags, grains in bulk, and various other materials, including farm equipment. The buildings are usually constructed of brick masonry, with tile roof and brick floor. The walls are usually covered with a layer of sand plaster. A cement and sand plaster is also used to cover the floor. Usually, there is no ceiling in the building. One narrow door and a small window on the front wall of the building are very common.

Summary

The traditional drying methods used by farmers in Northeast Brazil result in considerable loss of grain because they expose the grain to attack by both animals and insects. These methods, because of the climatic conditions in the region, do not achieve the moisture levels necessary for safe storage. Most of the grain storage facilities are also inadequate and do not prevent losses by rats, insects, and fungus infestations.

LITERATURE REVIEW

Grains constitute a major source of food for men and animals. According to USDA agricultural statistics (2), about 10.1×10^9 bushels of wheat, 2.6×10^{11} pounds of rice, and 8.5×10^9 bushels of corn were produced in the world in 1966. Most of this was used for food for man and domestic animals and for industrial processing. Grains are subject to losses that vary from country to country and from year to year.

Officials in the Food and Agriculture Organization (FAO) of the United Nations (10) estimated that 10 per cent of the stored grain in the world is lost annually. In Latin America it has been estimated that there is a loss of 25 to 50 per cent of harvested cereals and pulses. In certain African countries about 30 per cent of the total subsistence agricultural production is lost annually, and in areas of Southeast Asia some crops suffer losses of up to 50 per cent.

The losses begin at the field before the crops have been harvested. Birds, rodents, and insects are the principal pests that eat or spoil crops at the field prior to harvesting. Poor harvesting methods and transportation are also responsible for losses of grain.

Christensen and Kaufmann (9) pointed out that losses in both quantity and quality of stored grains occur as a result of rodents, insects, mites, and fungi. Their study was concerned primarily with problems caused by fungi and showed that fungi growing in stored grains cause decrease in germinability, discoloration of part or all of the seed, heating and mustiness, various biochemical changes, production of toxins, and loss in weight.

Bastos (5) evaluating damage caused by a cowpea weevil in Northeast Brazil, concluded that initially 27.8 per cent of the samples had over 5 per cent of the beans damaged. After 56 days of storage the percentage of samples with over 5 per cent damaged increased to 68.46 per cent. Samples with 5 per cent or more damage received a price reduction of 55.52 per cent.

Various experiments by Kelly (13) on the storage of grain have shown that the grain moisture and temperature are the most important factors considered for its safe storage. The maximum moisture content at which grain can be stored safely varies with the kind of grain, the locality in which it is stored, the method of conditioning, and the length of the storage period. The moisture content of grain also affects insect development. For shelled corn with less than 9 per cent moisture, the most destructive insects become inactive. Temperature is also a very important factor considered in storage of grains because it is important in the development of all organisms and its effect is correlated with the amount of moisture present.

Hall (10) pointed out that the temperature range between 20° and 40°C and relative humidity above 90 per cent provide the most favorable conditions for growth of most storage fungi. He also stated that the fungi which grow on grain stored at higher and lower temperatures or at lower humidities fall into fairly clearly defined groups.

Beetles and moths cause considerable grain damage in the tropics. According to the survey on world losses to cereals from pests conducted in 1947 by Hall (10), 50 per cent of the total annual loss could be attributed to insects. Mites are also after food in stored grain. They are not serious grain damaging agents, but they require the same environment as many other insects which cause considerable damage. The presence of mites is often an indication of the presence of the other insects.

A grain temperature of 22°C is considered optimum for development of insects. With few exceptions, temperatures above 35°C are unfavorable for insect reproduction. Temperatures lower than 15°C also inhibit insect development. At 27°C the development of some insects increases with the moisture but their development decreases with increased moisture when the temperature is higher than 27°C.

In tropical regions, rodents cause damage to grain in the field before harvest as well as to stored grain.

They consume grain and damage an even larger quantity with their excrement and destruction of containers. Grain in jute bags is most susceptible to rodent attack. There is less damage in bulk storing because rodents cannot burrow into bulk grain.

Special attention has been given in recent years to the methods and types of storage for grains in tropical climates. The storage environment, the conditioning and handling of grain, the extent of storage losses, and improved methods and systems of storage have been studied. Barre and Wimberly (4), studying the progress in better handling and storage methods for food grains in South Asia, advise the use of simple metal bins for low cost and long term storage of dry grain.

White et al. (22) studied the effects of storing soybeans at different temperatures. Soybeans dried with heated air were reconditioned to 12 and 17 per cent moisture and stored for six months at three different storage temperatures. They report that soybeans dried at higher temperatures are more prone to mold development, reduction in germination, and an increase in free fatty acid content. Roa et al. (18) investigated a number of natural drying methods and developed a system consisting of vertical trays for drying cassava.

Previous studies have shown that solar energy is feasible for various activities in agriculture, including grain drying. Because of the shortage and increasing cost of the principal drying fuels, solar energy has gained attention as a source of energy for drying grain. A solar drying system could be highly suitable for Northeast Brazil because of the large number of farms with no other sources of heat or mechanical energy.

Rugumayo and Bakker-Arkema (20) pointed out that tropical grain storage and aeration using solar energy appears feasible with no substantial grain deterioration for up to one year. In Brazil, 600 kg of beans were dried in only 3 days using a very simple and inexpensive flat plate solar collector (19).

SOLAR DRYER DESIGN

The process of low temperature grain drying can be considered adiabatic. This adiabatic drying process is characterized by a decrease in dry-bulb temperature of the air and an increase in the humidity. The enthalpy and the wet-bulb temperature remain practically constant.

The evaporation of the grain moisture is achieved by air, sometimes heated, passing through the wet grain. The sensible heat of the air is transformed into latent heat during the process of evaporation of grain mositure and its transfer to the air.

Objectives

The objective of this project is to design, develop, and test a grain dryer suitable for use on small farms in Northeast Brazil. The design will be based upon the following criteria:

1. The capacity should be equivalent to the daily harvesting capacity of one man.
2. The dryer should require no commercial forms of energy.
3. The dryer should be simple to construct and operate and be built from material available in Brazil.

4. The dryer should dry the grain to a storable condition.

Description

Solar energy might be an effective source of heat energy for a grain dryer with the required characteristics. The solar energy collector might be similar in design to one described by Buelow and Boyd (7). A cross section of this design is shown in Figure 1. It consists of one sheet of standard window glass, a metal absorbing plate, and an insulated bottom. The absorber is coated with a mixture of lampblack, asphalt paint, turpentine, and gasoline. The absorptivity coefficient of the absorber plate is estimated to be 0.98. The transmittance of the glass is 0.688.

The capacity for heating the air can be estimated from an equation developed by Buelow and Boyd (7). This expression is based on the energy balance relationship assuming steady state conditions, a uniformly distributed radiant energy constant with time, and negligible heat conduction in the absorber plate;

$$t_2 - t_1 = (IR/U)(1 - e^{-N}) \qquad [1]$$

in which

N = UAc/MC

Ac = collector area, m^2

R = incident solar radiation, cal/m^2-hr

U = overall heat transfer coefficient, cal/m^2 hr°C

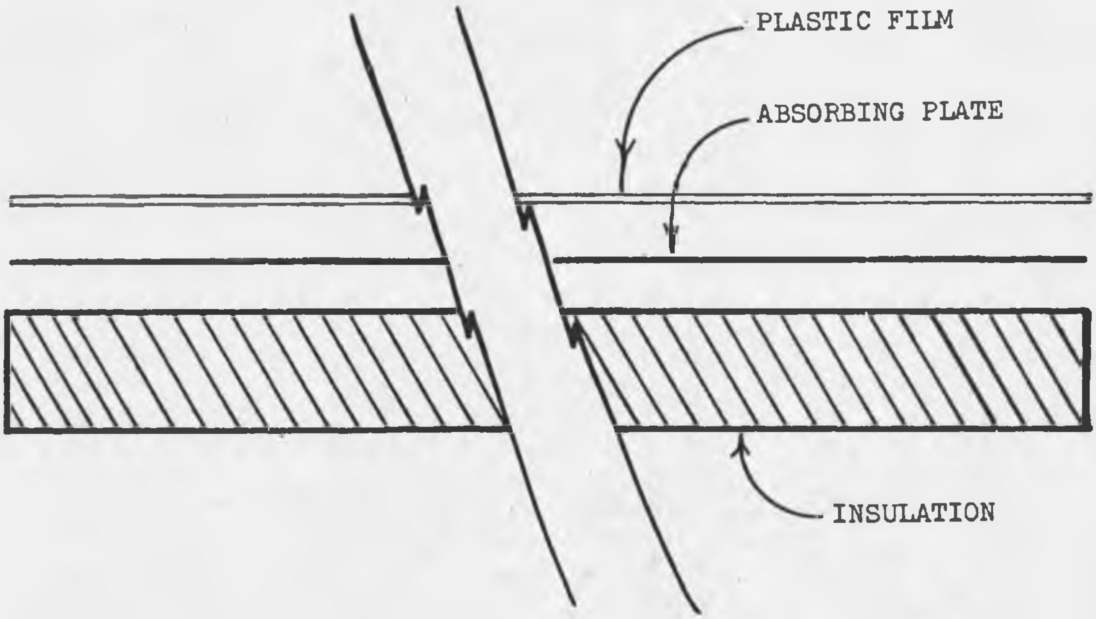

Figure 1. Cross section of solar collector.

M = mass flow rate of air, Kg/hr

I = fraction of incoming solar radiation which is absorbed by the absorber plate, 0.674

C = specific heat of air, cal/Kg dry air °C

t_1 = temperature of air entering the collector, °C

t_2 = temperature of air leaving the collector, °C

Figure 2 shows the general configuration of a solar drying system for small batches of ear corn. The dryer is situated above ground and consists of a collector, a drying chamber, and a chimney to promote air flow. The air to be heated passes through the air flow channels above and below the absorber plate and enters the lower part of the drying chamber below the slats. The air passes up through the slats and ear corn and exits through the chimney on the end of the chamber. The buoyancy force of heated air in the chimney will force air upward and provide continuous flow through the collector and the corn in the drying chamber.

To be suitable for use in Brazil, the dryer should be constructed with low cost materials available in the region. Mud block or brick masonry with lime mortar, wood, and used sheet metal would be appropriate for this use. They are cheap and farmers can use them without further training.

The dryer could be constructed above-ground with masonry walls. The heated air chamber would have a slatted

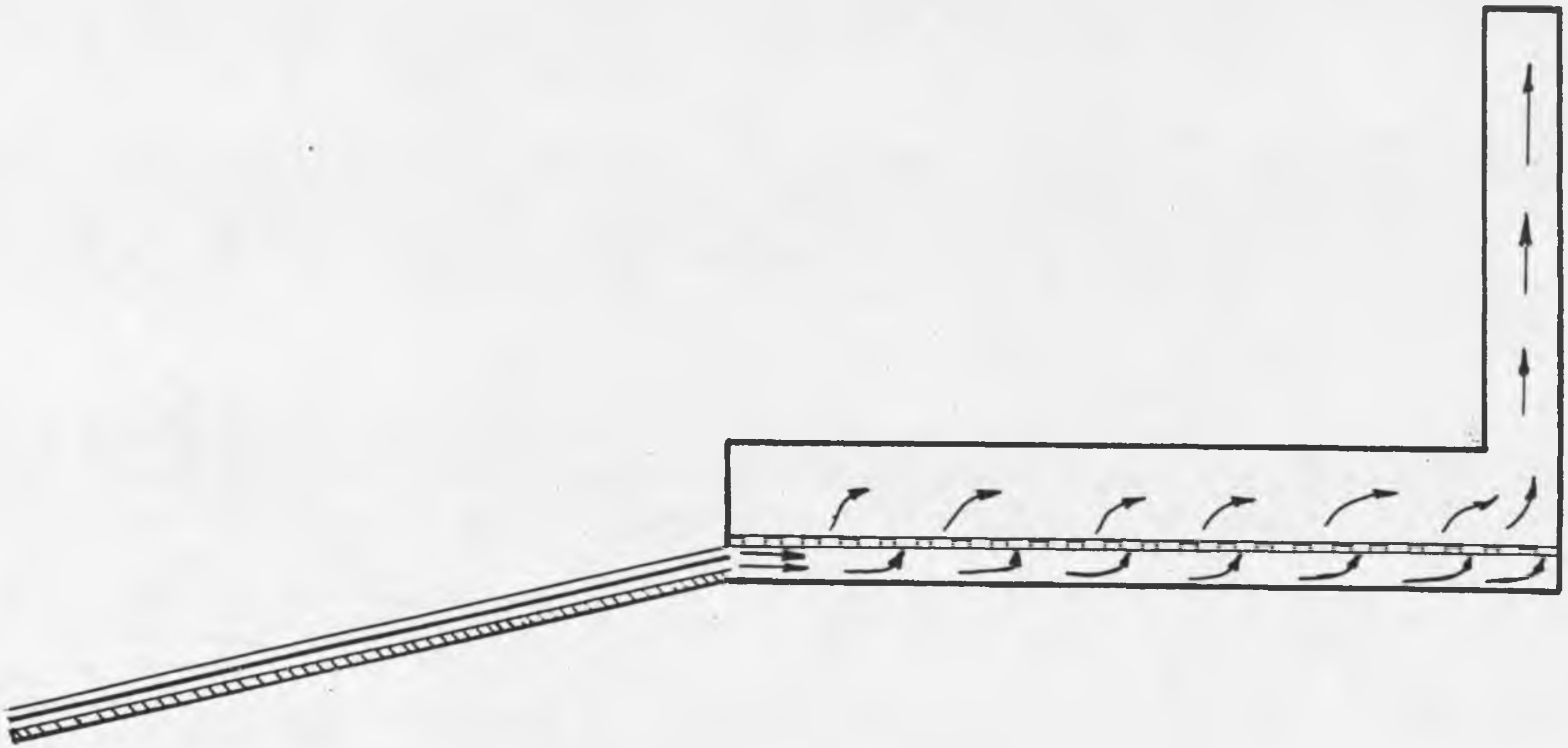

Figure 2. Cross section of solar grain drier.

floor made of wood, a stack chimney made of masonry or sheet metal. A horizontal door should be placed on top of the drying chamber for charge and discharge. Where prevailing winds occur, the dryer can be oriented with the collector on the windward side to take advantage of natural wind forces. Barre and Sammet (3) present a derived equation of air velocities induced by wind forces:

$$V = A\ E\ S \qquad [2]$$

in which

V = air flow, m^3/s

A = area of inlet, openings, m^2

S = wind velocity, m/s

E = effectiveness of openings (varies from 0.50 to 0.60 for perpendicular winds, to 0.25 to 0.35 for diagonal winds).

An equation for velocity of flow in a ventilation stack was derived based on the expansion and buoyancy force of heated air. The buoyancy force is proportional to the weight of the outside air displaced.

The energy available to induce air flow is related to the mass of the air in the stack.

The equation describing the relationship between natural ventilation rate and the parameters inducing air flow is:

$$V = 4.43\ A\ \Theta\ [(L(T_2 - T_1)/T_1)]^{1/2} \qquad [3]$$

in which

V = rate of ventilation, m^3/s

A = cross-sectional area of flue, m^2

L = vertical distance from inlet to top of stack, m.

T_2 and T_1 = inside and outside absolute temperatures

Θ = ratio of flow with friction and other losses to frictionless flow = 0.3 to 0.5.

The Theoretical Capacity

The harvesting capacity of one Northeast Brazilian farmer picking corn by hand is about 500 kg of ear corn per day. Corn might typically be harvested at 24 per cent wet basis and should be dried to 13 per cent wet basis. The initial design must necessarily be based upon a number of assumptions.

The maximum achievable drying rate will be limited by the diffusion rate of moisture within the corn kernel. That is, the drying air can receive moisture no faster than it is released through the surface of the kernels. Hustrulid and Flikke (12) show a close relationship between theoretical and experimental data for shelled corn in an air temperature of 43°C, a temperature within the range of that which might be expected in a solar drier (8). From a curve presented in their report, the average moisture content of corn would be reduced from 24 per cent to 13 per cent in about 12 hours. During this time, 500 kg of corn would lose about 57 kg of moisture for an average drying rate of 4.7 kg per hour.

The outside air in Northeast Brazil can be expected to be about 27°C and at 70 per cent relative humidity. This air would contain 0.755 g of water per grams of dry air. Heating this air to 43°C would reduce its relative humidity to 28 per cent. If, in the process of passing through the corn, the air took on 75 per cent of its potential increase in moisture holding capacity it would exhaust at about 30°C and 70 per cent relative humidity and would contain 0.0187 g water per gram of dry air, an increase of .0032 g/g. Thus, to remove 4.7 kg per hour from 500 pounds of corn, the air flow rate must be 1469 kg per hour or 0.35 m^3/s.

Considering 4.5 m as the maximum practical height for a chimney built by farm labor, the required cross sectional area for the chimney, using Equation [3] and a friction factor of 0.3 is:

$$A = \frac{0.35}{(4.43)\ (.3)\,[(4.5\frac{(30-27)}{300})]^{1/2}} = 1.25\ m^2.$$

Thus, on a 1.25 m wide unit, the 4.5 m chimney could be the same width as the collector and drying chamber and one meter in the other dimension.

These dimensions are an approximation at best, but identify the order of magnitude of the dimensions necessary for the 500 kg dryer. The drying curve is not linear with time so if all assumptions are correct, the drying rate would be limited by air flow at the beginning of the drying period and by diffusion within the kernels toward the end of the drying period.

The average insolation based on measurements in Northeast Brazil can be estimated at 746 Kcal/m^2hr. The desired temperature of 43°C will require a 16 degree rise. The overall conductance of the collector is 11.5 Kcal/m^2hr°C (7). Applying Equation [1] the required solar collector area to provide the temperature rise and air flow is:

$$A_c = \frac{MC}{U} \ln\left[\frac{IR}{IR - \Delta T}\right]$$

$$= \frac{(1469)(.245)}{11.5} \ln\left[\frac{(.674)(746)}{(.674)(746) - (11.5)(16)}\right]$$

$$= 14.26 \text{ m.}$$

The energy gained by the collector can be determined by the equation below:

$$Q = I\ R\ A_c \qquad [4]$$

where

Q = heat gain in collector, Kcal/hr

I = fraction of incoming solar radiation which is absorbed by the absorber plate, 0.674

R = incident solar radiation Kcal/m^2hr

A_c = collector area, m^2.

Based on the assumed conditions, Q = (.674)(746) (14.26) = 7170 Kcal/hr.

The total amount of heat required for the grain drying process is $Q_t = M(h_2 - h_1)$ where

M = mass flow rate of air, Kg/hr

$h_2 - h_1$ = enthalpy gain in drying air as it passes through the corn, Kcal/Kg of dry air.

For the assumed air flow and moisture uptake by the air, Q_t = 1469 (24.69 - 20.25) = 6522 Kcal/hr. So the collector is large enough to provide the energy required to dry the grain.

The collector should be oriented such that the inlet will face any prevailing winds. The average wind velocity at a station in Northeast Brazil is 4.83 m/s from June to December (6). Selecting arbitrarily the value 0.4 for effectiveness of openings and the inlet opening area equal to 1.25 m x 0.038 m = 0.047 m^2, estimated flow of air due to wind velocity would be 5.5 m^3/min. Wind may or may not occur during a drying period so the drier should be designed to operate with no assistance from natural air currents.

The dryer bed should be designed to support 500 kg of ear corn. The bulk density of ear corn is 400 kg/m^3 so for 500 kg of corn the required volumetric capacity of the drying bed is 1.25 m^3.

Selecting a 0.30 m depth for the drying bed and a 1.25 m width, the length is 3.3 m and the floor area is 4.15 m^2. Air flow rate through the corn = $\frac{.35 \times 60}{4.15}$ = 5 m^3/min m^2.

The pressure drop at this flow rate through one foot of clean ear corn as it would be when hand picked is .0025 inches of water which is equivalent to 0.0635 kg/m^2 (1).

The drying bed should be built with as much opening as possible to minimize resistance to air flow. This can be provided by building the floor of 2.5 cm x 5 cm boards set on edge spaced 3.5 cm apart and supported on dressed 2.5 cm x 10 cm boards set 0.60 cm on center. This floor will provide a high percentage of open area and is structurally capable of supporting 500 kg of ear corn.

The slatted floor is the top of the chamber into which the collector will discharge the hot air through an opening at one end. One side of this chamber can be hinged to permit easy cleaning or removing the kernels which drop through the slatted floor.

The chamber above the slatted floor should provide space for a 0.30 m depth of corn plus a few centimeters for passage of air to a chimney at the end opposite the collector. An air-tight door will be provided at the top for charge and removal of corn into the drying chamber.

The chimney with 1.25 m^2 of cross-sectional area and a height sufficient to bring the air exhaust level 4.5 m above the collector inlet could be built of masonry or other material available in the region. The walls can also be made of masonry built directly on the ground and should be located on an elevated site to prevent flooding in case of rain. Figure 2 shows a cross-section of the dryer.

TEST

Because of the uniqueness of this solar grain drying system, most theoretical design calculations are approximations at best. The air flow rate calculations based upon a natural ventilation system must involve gross estimates for related flow resistances. Most drying data on corn relate to shelled corn rather than the ear corn intended to be dried in this system. The 0.3 m depth of corn in this system is neither deep bed nor thin layer. Consequently, field testing is necessary to gain any performance characteristics of a solar drying system for ear corn using buoyancy as the driving force for air flow.

To test the concept and gain preliminary performance data, a prototype dryer was constructed at Campbell Avenue Farm in Tucson, Arizona, in January, 1977 (Figure 3). Because the dryer is intended for applications in Brazil, data from tests in Arizona will not be directly applicable to the intended conditions. One striking difference lies in the solar zenith, requiring a much steeper collector orientation in Tucson than would be appropriate in Brazil. Thus, for a given elevation difference between the collector inlet and chimney outlet positions for air flow, a system designed for Tucson has a much larger elevation difference within the collector and a lesser difference within the chimney. The

Figure 3. Proto dryer for tests at Campbell Avenue Farm.

chamber being horizontal, its dimensions can be the same for both locations.

The prototype was built somewhat smaller than a full scale 500 kg unit for a Brazil farm. The solar collector was patterned after the design by Buelow and Boyd (7) and consisted of a 1.2 x 2.4 m sheet of 28 gauge galvanized sheet steel painted black with flat black paint. The steel sheet was supported by the frame on each edge and midway between the edges to separate it from a clear vinyl plastic cover on the top and 12 mm of corkboard insulation on the bottom, forming a 19 mm deep air flow channel above and below the collecting surface (Figure 1).

The 1.2 m by 1.5 m drying chamber was constructed of plywood insulated with corkboard. The slatted floor for supporting the corn 7.5 cm above the bottom of the chamber was built of 2.5 cm x 5 cm lumber spaced 3.7 cm as described previously. The chimney was also constructed of plywood and provided a vertical air channel 1.2 m wide by 0.15 m. The chimney extended 0.90 m above the drying chamber for a total inlet to outlet elevation differential of 2.14 m.

The solar collector faced directly south and tilted 42° to the horizontal, based on Tucson latitude of 32 degrees plus 10 as recommended by Kreider and Kreith (14). The bottom edge of the collector was 0.60 m above the ground surface.

Unfortunately ear corn for testing was impossible to locate in Southern Arizona at the time the tests were to be conducted. The most nearly suitable substitute was fresh picked sweet corn purchased in Nogales, Mexico. This ear corn was placed on the slatted floor in the chamber to a depth of approximately 0.30 cm.

Air temperatures and relative humidities were recorded at three locations within the system; namely at the collector inlet, in the hot air chamber at the collector outlet, and at the entrance to the stack. These are recorded in Table 3.

Air flow rates were determined by periodic measurements of air velocity in the stack with a Hastings air velocity meter. The air velocity was very difficult to measure with any degree of precision because of the continuous fluctuation of indicated velocity. The velocities, as recorded in Table 4, are the maximum and minimum velocities observed while measuring the flow rate at the geometric center of the stack over about a 1-minute period of time.

To estimate an air flow rate, the average of the maximum and minimum was used as representative of the velocity at the center of the stack. At the temperatures and flow rates observed, the Reynolds Number is less than 2130 suggesting streamline flow. For streamline flow, the average velocity for the cross section is about 0.5 times

Table 3. Temperature, relative humidity measured at collector inlet, collector outlet, and hot air chamber for the first and second day of test.

Time of day (hr)	First day of testing						Second day of testing					
	Collector inlet		Collector outlet		Hot air chamber		Collector inlet		Collector outlet		Hot air chamber	
	t (°C)	RH (%)	t (°C)	RH (%)	t (°C)	RH (%)	t (°C)	RH (%)	t (°C)	RH (%)	t (°C)	RH (%)
9.00	7	90	6	92	6	100	6	81	0	100	2	91
10.00	11	87	14	68	13	82	9	78	11	69	9	86
11.00	12	85	21	46	21	46	11	66	17	47	16	54
12.00	14	81	28	43	27	36	14	40	32	15	27	30
1.00	15	55	39	14	33	26	16	30	42	9	33	22
2.00	16	52	40	9	36	25	17	27	52	7	39	18
3.00	16	46	48	8	38	22	17	25	52	7	41	15
4.00	16	40	44	9	35	24	17	25	47	8	39	15
5.00	14	41	38	11	31	25	15	25	38	9	33	18

Table 4. Rate of water removed, rate of air velocity, moisture content during the first and second day of the test.

Time of day (hr)	Kg water / Kg air (x 10^{-3})	Cross section av. velocity (m/min)	Specific volume of air (m^3/Kg)	Rate of water removed (Kg)	Water rem. accumulated (Kg)	Moisture content (%)
			First day			
9.00	.28	3.4	.87	.012	.012	30.9
10.00	.57	3.8	.89	.026	.038	30.7
11.00	.00	4.3	.92	.000	.038	30.7
12.00	.36	5.5	.94	.023	.061	30.6
1.00	2.28	6.7	.95	.174	.235	29.5
2.00	3.78	7.6	.96	.327	.557	27.6
3.00	3.50	7.0	.97	.273	.830	25.8
4.00	2.57	6.4	.96	.185	1.015	24.7
5.00	2.43	5.8	.93	.164	1.179	23.6
			Second day			
9.00	-.85	3.8	.85	-.041	-.041	23.33
10.00	.57	4.7	.88	.033	-.008	23.07
11.00	.71	5.7	.90	.049	.041	23.01
12.00	2.43	6.2	.94	.173	.214	21.42
1.00	3.43	6.6	.95	.257	.471	19.42
2.00	4.48	6.9	.97	.344	.815	16.69
3.00	4.28	6.5	.98	.307	1.122	14.04
4.00	3.43	5.7	.96	.220	1.342	12.02
5.00	1.86	4.9	.95	.104	1.446	11.05

the peak velocity (11). Consequently, the average air velocity in the stack at any time was assumed to be one-half the average of the measured maximum and minimum readings at the center of the stack. These values are also recorded in Table 4. From these temperatures, relative humidities and air flow rates, the rate of transfer of moisture from the corn to the air was calculated.

The sample of corn was dried in the solar dryer over a two-day period. The corn was weighed initially and twice each day by removing it from the dryer and weighing it on scales to monitor moisture removal. Moisture percentages as determined by calculation from conditions of incoming and exhaust air are shown in Table 4.

The air velocities throughout the two days of test are plotted in Figures 4c and 5c. The days were quite similar in weather and temperature so the air flow curves are also quite similar.

Figures 4b and 5b show curves of the rate of moisture removal from the corn during the two days of drying as determined by the measurement of air flow and moisture content of the air. Figures 4a and 5a show the cumulative moisture removal for each day, again based upon the stage changes of the air as it passed through the system.

Based upon corn weights taken at 9 a.m. and 5 p.m. of each day, the corn moisture percentage began at 31.7 per

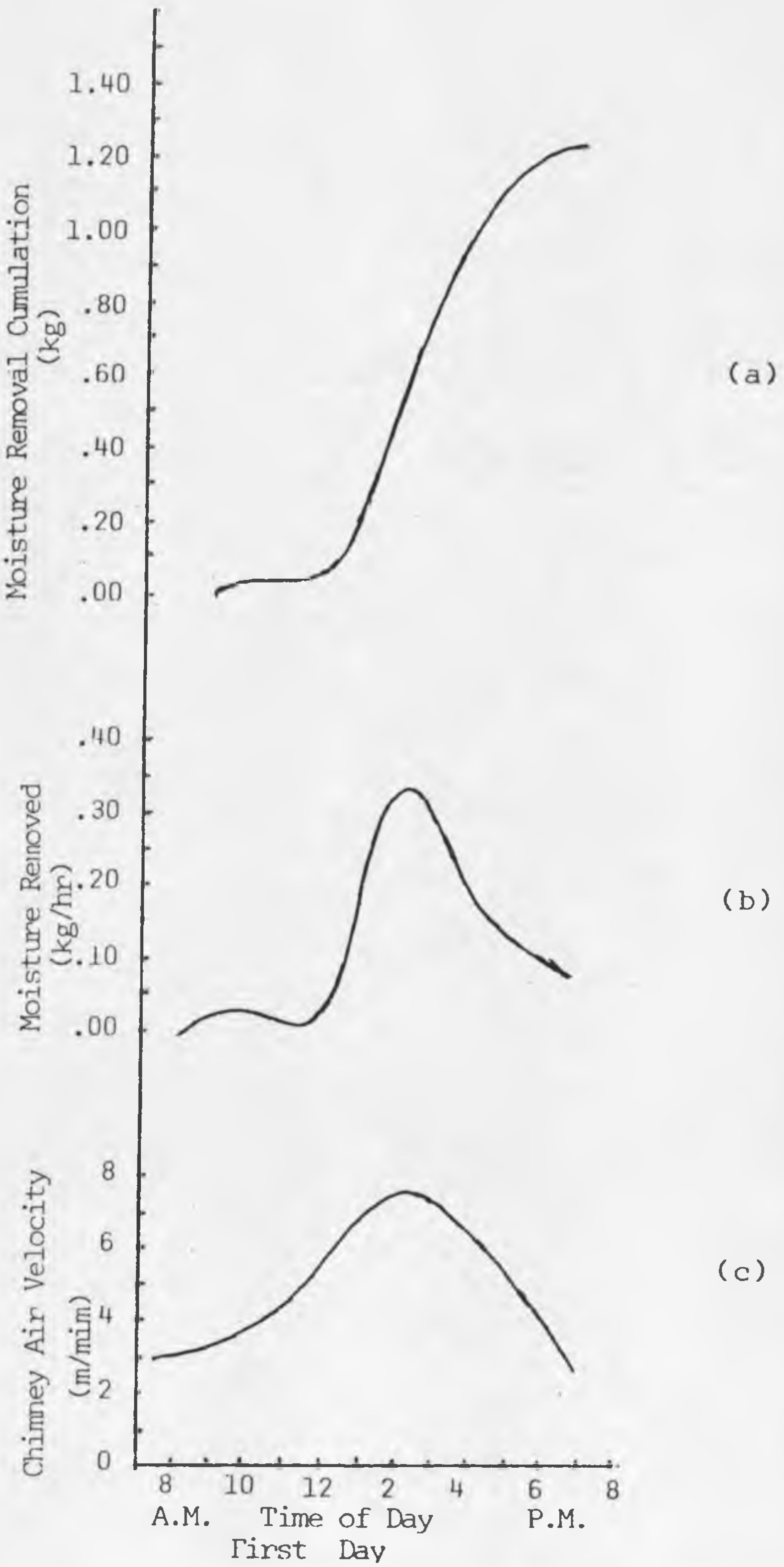

Figure 4. Moisture removal and chimney air velocity during first day of test.

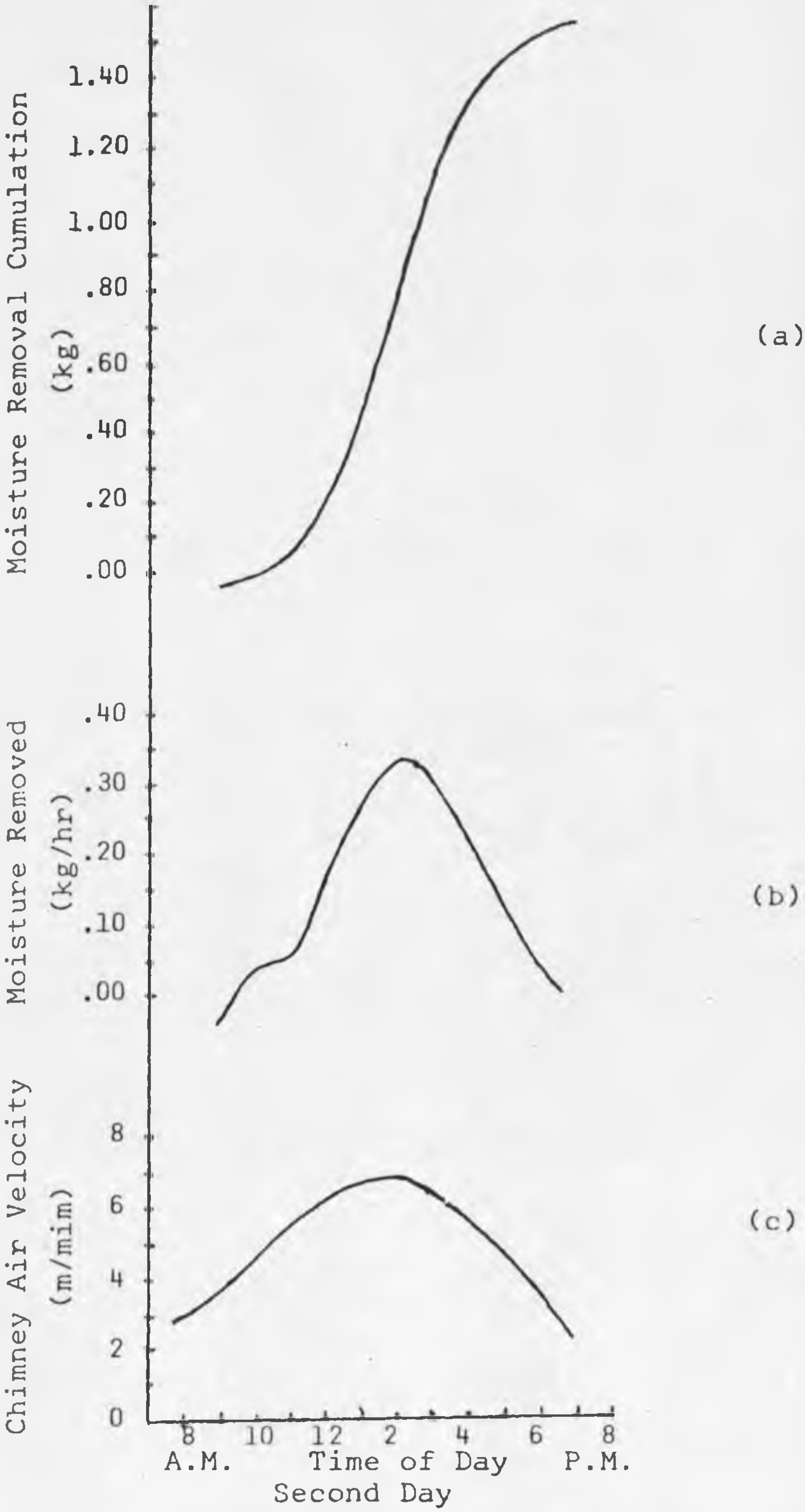

Figure 5. Moisture removal and chimney air velocity during second day of test.

cent wet basis and 1.19 kg of water were removed during the first day of drying to reduce the moisture percentage to 23.6 per cent. This measurement corresponds very closely with the amount removed as determined by air state changes. An additional 0.13 kg was removed between 5 p.m. of the first day and 9 a.m. of the second day. During the second day, 1.0 kg was removed for a final moisture percentage of 15.0 per cent. This second day measurement does not agree with the corresponding measurement of moisture added to the drying air. The value based on moisture removed is likely the more nearly correct because of the more direct nature of the measurement. It is also unlikely that more moisture would be removed from the corn during the second day than during the first as suggested by the measurements in the air, especially in view of the similarity of drying conditions during the two days of the test.

Conclusion

Although many of the factors from which an effective solar grain dryer for Northeast Brazil farms could be designed remain unknown, the concept appears sound. The buoyant forces generated by heating the air in a solar collector provide a movement of air through the system and remove moisture from the corn.

The drying system is relatively simple and can be constructed of materials available to the farmers in the area. Two or more dryers may be required for a farm, each with a capacity of one day's harvest. With the system, the farmers can harvest their corn earlier, thus protecting it from field damage by insects and rodents. They can then dry it to transform it into a more easily stored product, thus substantially increasing their total net harvest from each year's crop.

Before an appropriately designed drying system can be made available to the farmers, additional information is necessary. Tests should be conducted in the Brazilian climate to determine recommended dimensions of collector, drying box, and stack for appropriate balance of these components. Improved collectors, as they become available, should be tested for their effectiveness in this particular application. The provisions for loading and removing the corn from the drying box need improvement to reduce labor and maximize convenience. The possibility of increasing air flow by collecting solar heat in the stack should also be investigated.

REFERENCES

1. Agricultural Engineering Yearbook. 1975. American Society of Agricultural Engineering. St. Joseph, Michigan.

2. Agricultural Statistics. 1967. USDA. Washington, D. C.

3. Barre, H. J., and L. L. Sammet. 1950. Farm Structures. 3rd ed. John Wiley and Sons, Inc., New York.

4. Barre, H. J., and James E. Wimberly. 1975. Storage of Food Grain in South Asia. ASAE Annual Meetings, Davis, California, Paper No. 75-4056.

5. Bastos, Jose A. M. 1973. Avaliacão dos Prejuizos Causados pelo Gorgulho em Amostras de Feijão de Corda Colhidas em Fortaleza, Ceará. Pesquisas Agropecuárias Brasileiras, Série Agronômica 8:131-132.

6. Boletim Agro-Meteorológico. 1972-1975. Centro de Ciências Agrárias, Universidade Federal do Ceará. Fortaleza, Ceará, Brasil.

7. Buelow, F. H., and J. S. Boyd. 1957. Heating Air by Solar Energy. Agricultural Engineering, January, pp. 28-30.

8. Chittenden, D. H., and Andrew Hustrulid. 1966. Determining Drying Constants for Shelled Corn. Transactions of the ASAE. 52-55.

9. Christensen, M. C., and H. H. Kaufmann. 1969. Grain Storage. University of Minnesota Press, Minneapolis.

10. Hall, D. W. 1970. Handling and Storage of Food Grains in Tropical and Sub-tropical Areas. Food and Agriculture Organization of the United Nations. Rome.

11. Henderson, S. M., and R. L. Perry. 1966. Agricultural Process Engineering. 2nd ed. Library of Congress Catalog Card Number 54-12684. USA.

12. Hustrulid, A., and A. M. Flikke. 1959. Theoretical Drying Curve for Shelled Corn. Transaction of ASAE. 112-114.

13. Kelly, C. F. 1941. Temperature of Wheat in Experimental Farm-type Storage. USDA. Circ. 587.

14. Kreider, J. F., and F. Kreith. 1975. Solar Heating and Cooling. McGraw-Hill Book Company, New York.

15. Paiva, R. M., S. Schattan, and C. F. T. Freitas. 1973. Brazil Agricultural Sector Economic Behavior, Problems and Possibilities. XV International Conference of Agricultural Economists. S. Paulo, Brazil.

16. Patrick, George F. 1972. Desenvolvimento Agrícola do Nordeste. IPEA/INPES Rio de Janeiro, Brasil.

17. Perspectivas de Desenvolvimento da Agricultura do Nordeste. 1971. IX Ruinião da Sociedade Brasileira de Economistas Rurais. Fortaleza, Ceará, Brasil.

18. Roa, G., F. W. Bakker-Arkema, L. Johnson, and J. V. Beek. 1974. Drying Cassava. ASAE Annual Meeting. Stillwater, Oklahoma, Paper No. 74-3037.

19. Roa, G., and I. M. Carvalho. 1976. Drying of "Carioca" Dry Beans with Solar Energy in a Stationary Bin. ASAE Annual Meeting, Lincoln, Nebraska, Paper No. 76-3021.

20. Rugumayo, E. W., and F. W. Bakker-Arkema. 1975. Tropical Grain Storage with Aeration Using Solar Energy. ASAE Annual Meeting. Davis, California. Paper No. 75-4061.

21. Sinopse Preliminar do Censo Agropecuário. 1970. Instituto Brasileiro de Geografia e Estatística. Rio de Janeiro, Brasil.

22. White, G. M., O. J. Lower, I. J. Ross, and D. B. Egli. 1975. Storage Characteristics of Soy Beans Dried with Heated Air. ASAE Annual Meeting, Davis, California, Paper No. 75-4059.