A STRAW-FIRED FURNACE FOR GRAIN DRYING PURPOSES

by

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INTRODUCTION

The process of grain drying is almost as old as the civilization itself. Different types of artificial grain driers have been developed by man and others are still in the process of being developed. Most drying research is on large scale or commercial-type grain driers which require well-trained operators and highly sophisticated instrumentation. Development of a small and inexpensive grain drier to be used by the farmers especially in the third-world countries is undoubtedly imperative. There has been some recent research in this area but mostly with wood as fuel. The abundance of wood throughout the world, its comparatively rapid growth and reproduction, and the ease of obtaining supplies made it one of the earliest and most used of all fuels. Nowadays however, it is only of importance as fuel in those developing countries where large forests abound. In fact, firewood is not readily available in poor countries and if available, it is very costly (Lindblad and Druben, 1977).

Sundrying of grain is the predominant practice in Southeast Asia because most of the farmers cannot afford to buy a heated-air drier of any kind. In some countries, solar drying cannot effectively be used because the atmospheric relative humidity is too high most of the time. Sundrying seems impractical in the Philippines, since the harvest season usually coincides with the later part of the rainy season. During this time of the year, about 45 percent of the total rice production is harvested under an ambient temperature of

82°F and humidity of 85 percent (NEDA, 1975). Since grain is a hygroscopic material, it absorbs or gives off moisture depending upon the surrounding conditions. Grains may well become moldy during this time of the year. In addition, moisture sorption process of grains exposed to rain or high humidity has proven to cause fissures resulting in breakage during milling of rough rice (Kunze, 1967 and Stahel, 1935). Samson and Duff (1973) found that artificially dried rough rice gave almost equal milling recovery as sundried. The amount of whole grain from sundried samples however, was much lower than from artificially-dried samples (46 vs 58 percent).

It has long been recognized that improper drying of harvested grain is an important cause of post-harvest losses on the farm. The introduction of improved farming techniques such as early-maturing varieties of grain, effective insecticides & herbicides, efficient use of fertilizers and double cropping in irrigated areas resulted in a tremendous increase in the production of grains all over the world. Apparently, grain losses increased too, and drying methods did not improve with the increase in production. To keep pace with the production, the farmers harvest and dry their crops even under adverse weather conditions. This situation could be remedied by the introduction of an artificial grain drier that is inexpensive and simple and requires construction materials that are readily available in most farms.

C.J. Moss (1965) observed that: a) more than two-thirds of the population of the world depend on rice for food; b) one-third of the rice crop harvested is wasted because of inadequate treatment and storage; and c) it is necessary to develop simple equipment for drying rice to prevent this loss of food. Rice harvested with a high moisture content (18 to 22 percent) should be dried as soon as possible after harvest. Drying should begin within 12 hours of harvest and not later than 24 hours. Furthermore, drying temperature should range from 100 to 130°F (Cooperative Extension Service, Circular 476 Rev.).

In countries where fossil fuels (gas, diesel oil, etc.) are imported, the use of imported and locally-made grain driers utilizing these sources of heat is more expensive compared to the conventional and local drying practices. Besides, these driers are sold at high initial costs; thus, they are beyond the reach of most farmers. It is necessary therefore to test and try different types of drier utilizing indigenous sources of fuel. If this can be done, then the farmer can avail himself of the benefits that may be derived from drying grains through artificial means.

Generally, fuels that ignite at relatively low temperatures, burn rapidly and are easily obtained in large quantities at relatively low prices are desired. One such possible heat source is straw. Straw is replenished every year in the farm. In contrast, wood requires several years of growing season. The production of one kilogram of grain always results in production of a corresponding amount of straw (Moller, 1977). In addition, the heating value of 15 percent moisture wheat straw is about 6680 Btu per lb (Moller, 1977) which is not far below that of wood which is 7100 Btu per lb (Brooker, et al., 1974).

OBJECTIVES

The main objectives of this research are to:

(1) design and construct a furnace with inexpensive material considering wheat straw as fuel;

(2) design and construct a direct-fired grain drier; and

(3) evaluate the performance of the furnace and drier.

Secondary objectives are to determine the:

(a) rate and method of fuel feeding that will give;

1) a maximum temperature of 130°F below the drying floor, and

2) a minimum fluctuation of drying air temperature;

(b) drying capacity, drying efficiency and quality of the flue gases (evolution of carbon monoxide) as affected by;

1) grain bed thickness (2", 4", & 6"), and

2) effect of turning the grain (no turning vs turning every one hour and every 4 hours).

REVIEW OF LITERATURE

In a grain drying system utilizing heat from a furnace, the designer should give proper consideration to an optimal furnace design. Johnson and Auth (1951) listed the design requirements of a good furnace as follows:

(1) suitable openings must be provided for the introduction of the fuel and air, but they must not permit air leakage;

(2) furnace dimensions should be of such a nature as to permit sufficient space for complete combustion;

(3) impingement of the flame on any part of the furnace should be avoided;

(4) combustion and temperature conditions in the furnace should be such that no deposit of slag in the furnace occurs, unless the design requires it to be deposited;

(5) wall construction should meet the following requirements:

   a) the design and material of the furnace lining should be resistant to expansions and contractions due to temperature changes, temperature gradients, and load changes;

   b) insulation of the furnace should be provided to prevent heat losses;

   c) construction should be such as to prevent air leakage into the furnace;

   d) the furnace should have minimum maintenance; and

   e) the walls of the furnace should be of sufficient strength so that they are secure against failure in case of puffs within the furnace;

(6) passages must be provided for the proper transporting of the products of combustion from the furnace before temperatures are reduced to a point where flow is inhibited;

(7) means must be provided for the elimination of fly ash, ashes, or slag formed and deposited in the furnace; and

(8) adequate doors should be provided for access, inspection and lancing.

In a natural air convection system, the flow of flue gases is ensured by proper design of the chimney. Kinealy (1906) claimed that the chimney must be high enough to create sufficient draft in the furnace. Draft depends on the height of the chimney, the temperature of the hot gases inside, temperature of the cold air outside and to some extent, direction, velocity and humidity of outside air. If the draft is expressed in inches of water, it is found that the draft created by a chimney varies from 0.005 to 0.007 times the height of the chimney in feet.

Sneeden and Kerr (1969) came-up with an equation to estimate the draft in the form of:

$$D = 353h(1/T_{air} - 1/T_{gas})$$

where D = draft in mm of water

h = height of chimney in feet

T_{air} = atmospheric air temperature (^{o}K)

T_{gas} = flue gas temperature at entry to chimney (^{o}K)

The volume of a furnace should be such that sufficient heat is released after combustion so as to keep the inside furnace temperature high. Johnson and Auth (1951) recommended 35000 Btu per cu ft of furnace space per hour for most power plants using coal as fuel. However, for a grain drier furnace using pulverized rice hull as fuel, Ginzburg (1958) suggested a rate of 1430 Btu per cu ft of furnace volume per hour. To obtain a good quality product, the drying air temperature in contact with the grain must be limited to approximately 130°F. This restriction demands a lower heat release rate for a grain drier furnace compared to a power plant.

I. COMBUSTION THEORY

Combustion is defined as the chemical reaction between oxygen and various substances like carbon, hydrogen and sulfur associated with a release of heat.

Lister and Harris (1925) explained that when fuel is put into the fire, first the volatile constituents are driven-off in the form of gases. The hydrogen present in the fuel combines with oxygen to form steam. The carbon also combines with oxygen to form either carbon monoxide or carbon dioxide depending on the availability of oxygen. If the air supply is very much restricted, some carbon will pass out unburnt. The heat generated during combustion raises the temperature of the flue gases including the inert nitrogen and excess oxygen. Fuels are generally composed of hydrogen, carbon and sulfur. The equations of combustion are:

$$C + O_2 \longrightarrow CO_2$$

$$2C + O_2 \longrightarrow 2CO \text{ (partial combustion)}$$

$$2H_2 + O_2 \longrightarrow 2H_2O$$

$$S + O_2 \longrightarrow SO_2$$

Araullo et al. (1976) gave a formula for calculating the weight of oxygen required for complete combustion:

$$Wo = 2.67C + 8(H - \frac{O}{8}) + S$$

where Wo = weight of oxygen, lb/lb fuel

C, H, O and S = percentages based on the ultimate analysis of the fuel, in decimal.

Johnson and Auth (1951) reported that a typical analysis for straw is: carbon = 36 percent, hydrogen = 5 percent, oxygen = 38 percent, nitrogen = 0.5 percent, moisture = 15.75 percent and ash = 4.75 percent.

II. DRYING PRINCIPLES

After harvesting, grains should be dried to a moisture content that is safe for storage. Dry grain is less susceptible to fungus damage, deterioration of chemical components and loss in nutritive value. Grain drying can be accomplished in many ways. Basically, they fall into three general categories, namely: sundrying, natural and heated-air drying (artificial drying). Heated air drying uses some heat source to raise the temperature of the drying air. Lindblad and Druben (1977) reported that artificial drying results in more income for the farmers due to the following reasons: a) crops can be harvested earlier and farmlands become ready for the next crop sooner; b) grain losses due to long natural drying are minimal; and c) grains are kept in storage longer and taken out at relatively better condition.

Theory of drying. Drying is a process of simultaneous heat and mass transfer. The heat is required to evaporate the moisture which is removed from the drying products' surface by the external drying medium, usually air. Movement of water vapor into and out of grains has been studied by a number of investigators (Chung, 1967), (Hendersen, 1961), and (Smith, 1947). In general, grain moisture tends to evaporate when the grain has a higher vapor pressure than the surrounding air while the grain absorbs moisture if the pressure situations are reversed.

The concept of equilibrium moisture content is important in understanding the drying phenomenon. The equilibrium moisture content is reached when the grain moisture and surrounding water vapor pressure are equal. Angladette (1965) reported that ambient air-grain moisture equilibrium in a closed container depends ultimately on four factors: a) relative humidity of the air, b) moisture content of the grain, c) air temperature, and d) grain temperature. Secondary factors such as permeability or porosity of the grain and texture of the various parts of the grain also determine, to some extent, the equilibrium moisture content of the grain.

In the experiments carried out at the Centre National d' Etudies et d' Experimentation du Machinisme agricole (CNEEMA)(1958), the differences in grain moisture for the same relative humidity were found to be about 0.5 percentage point for every 10^{o}C difference of the drying air. To determine the relationship between the equilibrium moisture content of grain and the relative humidity of ambient air at constant temperature, Hendersen (1961) and Chung (1967) came up with the following equations, respectively:

$$(1)\ 1 - rh = e^{-CTMe^{n}}$$

$$(2)\ \ln(rh) = -\frac{A}{RT} e^{-BMe}$$

where rh = relative humidity, decimal

Me = equilibrium moisture content, percent (db)

T = absolute air temperature, °R

R = universal gas constant

C, n, A, and B = constants

For any drying condition, the equilibrium moisture content of grains could be predicted from these equations.

Heating the air reduces the relative humidity which increases the air's drying potential. If the temperature of the air is increased by 52°F, the relative humidity is reduced to about one-half. For example, if air with a temperature of 84°F and a relative humidity of 90 percent is heated to 136°F, the resulting relative humidity will be 45 percent (Psychrometric chart).

The drying rate is dependent on the temperature of the drying air and its relative humidity. Airflow rate and grain moisture content also affect the rate of evaporation (Hall, 1957). A number of physical mechanisms have been proposed for describing the transfer of moisture in grains (Brooker, et al., 1974): (1) liquid movement due to surface forces (capillary flow); (2) liquid movement due to moisture concentration differences (liquid diffusion); (3) liquid movement due to diffusion of moisture on the pore surfaces (surface diffusion); and (4) vapor movement due to moisture concentration difference (vapor diffusion).

Drying process can be divided into two periods: (1) the constant-rate period and (2) the falling-rate period. Hall (1957) explained that in the constant-rate period, drying takes place from the surface of the grain and is similar to evaporation of moisture from a free-water surface. The point marking the end of this period occurs when the rate of moisture diffusion within the product decreases below that necessary to replenish the moisture at the surface. The falling-rate period immediately follows. It is controlled largely by the product and involves the movement of moisture within the material to the surface by liquid diffusion and removal of moisture from the surface.

According to the depth of bed, the drying process can be divided into two categories - thin-layer drying and deep-bed drying. Thin-layer drying refers to the drying of grain which is entirely exposed to the air moving through the product. The equation representing movement of moisture could be based on Newton's law of heating or cooling i.e., the rate of drying is proportional to the difference between grain moisture content and the equilibrium moisture content, $dM/dt = -k(M - Me)$ (Hukill, 1947). When integrated, this becomes $MR = e^{-kt}$, where MR is the moisture ratio (M-Me/Mo-Me), *t* is drying time in hr and *k* is a constant. This equation is commonly known as the thin-layer drying equation.

Hendersen and Perry (1976) defined deep-bed drying as a process in which there is a finite moisture gradient through the drying layer at any time except zero. Material depths of 6 inches to many feet constitute deep beds. Depths of as small as one inch, however,

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provide evidence of the existence of moisture gradient and thus may be termed deep beds.

Brooker, et al. (1974) and Henderson and Perry (1976) explained that at the start of the drying process, a drying zone exists at the bottom of the bed. As drying continues, the zone passes entirely through the grain and the entire mass is dried to the equilibrium moisture content with the drying air.

Two gradients exist across the drying zone; a moisture content gradient and a temperature gradient. If the bed of grain is shallow and/or the air velocity is high, the drying zone may extend completely through the bed. The desired final average moisture may be reached before the bottom grain layers have reached equilibrium with the drying air.

Optimum drying air temperature and relative humidity. Lindblad and Druben (1977) found that high drying air temperature caused the kernels of some grains to pop. Breaking, cracking, and discoloration of grains occurred when corn and rice were exposed to high temperatures. The researchers, then, recommend a temperature range of 40 to 45°C (104 to 113°F) for drying rough rice.

Schmidt and Hukill (1956) investigated the effect of temperature and humidity of drying air on the milling yield of four varieties of rice: Caloro (short grain), Zenith (medium grain), Bluebonnet and Rexoro (both long grains). These were dried in thin layers in one continuous operation at air temperature ranging from 32 to 61°C, and relative humidities from 9 to 84 percent. The velocity of the air passing through the rice in one drying chamber was 30 m/min and in the other 60 m/min. Statistical analysis of the drying data showed that the losses in head rice yield were related more closely to the rate of moisture diffusion than to the temperature of the drying air.

Angladette (1965) reported that the color, cooking quality and flavor of rice varied according to temperature and humidity. He found that the drying air temperature which produced the best grain color, better separation of the cooked rice grains and good taste was between 47 and 59°C (117 to 138°F). Japanese findings (1956) indicated that storage at low temperatures (10 to 15°C) and high relative humidity (70 to 80 percent) preserved the quality of rice better than at normal temperatures. The nutrient losses were also reported to be less.

III. FARM GRAIN DRIERS FOR DEVELOPING COUNTRIES

To avoid the high cost of imported grain driers and fuel oil, a series of farm scale driers utilizing farm waste products have been developed for poor countries especially for those where the climatic conditions are unfavorable for natural drying of agricultural products.

One of these is "Brook's" drier (Fig. 1) which is being used in Nigeria and Africa to dry groundnuts and maize. This drier has a simple heat exchanger (3-55 gal. oil drums), and uses wood as fuel (Brook, 1964). Hot air rises through the drying floor by natural convection. Ryu (1976) found that "Brook's" drier could be made more efficient by increasing the height of the drying floor and size of the air inlet without increasing the amount of fuel.

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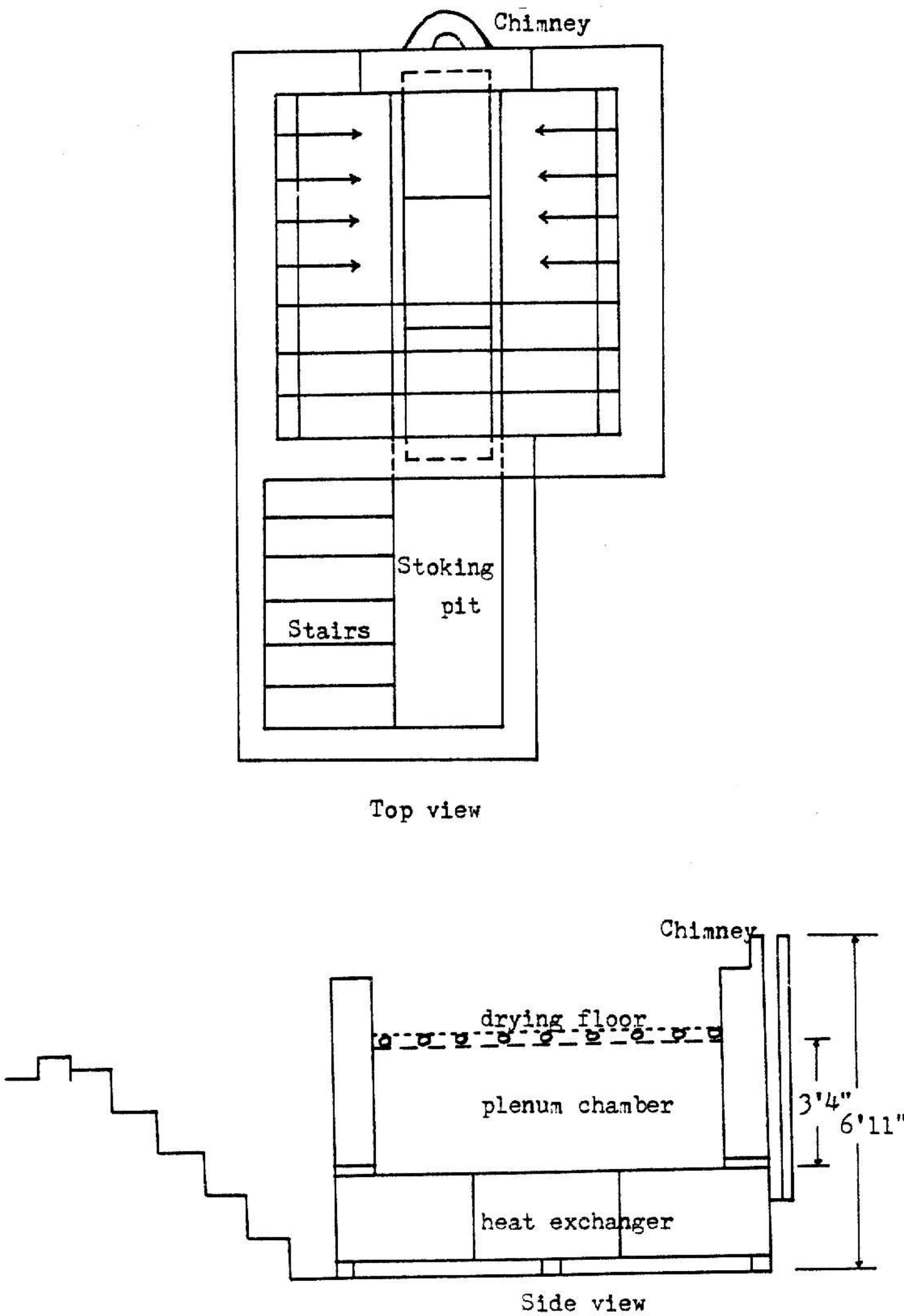


FIG. 1. BROOK'S DRIER (1964)

He came up with an equation to predict the air-flow rate through the grain bed:

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

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

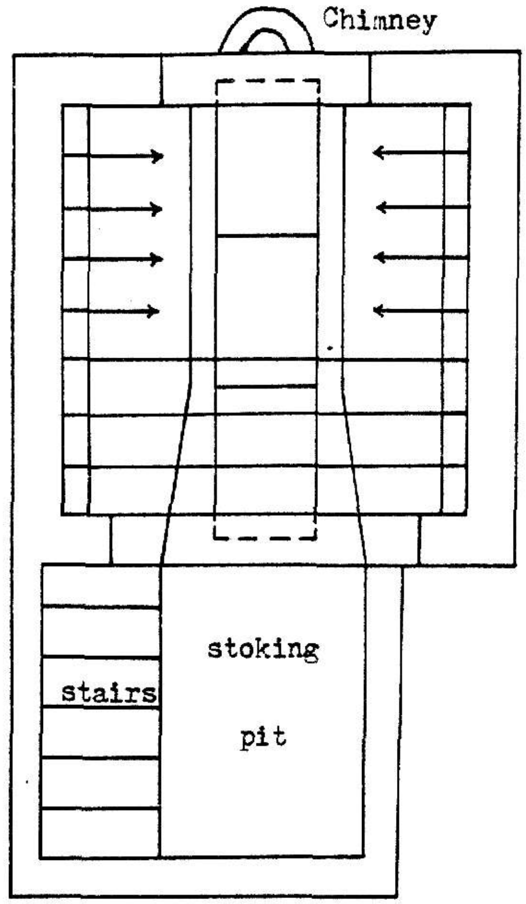
H = the height of the drying floor from the center of the flue, inches

dT = the temperature rise from the inlet to the mean plenum temperature, ^{o}K

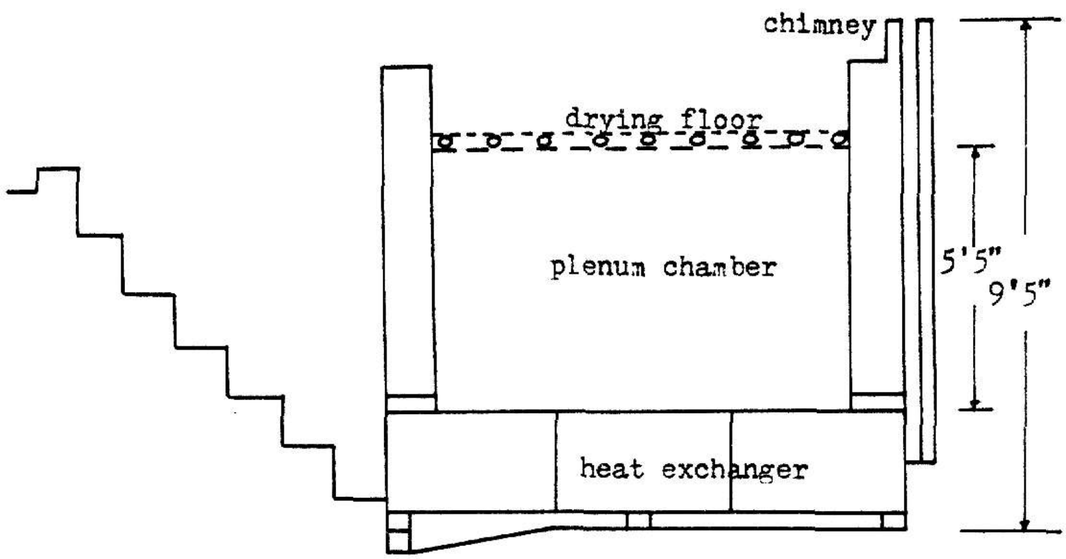
D = the grain depth in bed, inches

Based on Ryu's suggestions, Bolduc (1978) modified "Brook's" drier. He compared the drying performance of unmodified and modified "Brook's" drier (Fig. 2). The modifications were: a) the floor height was increased from 3'4" to 5'5" above the flue, b) the air inlet was increased from 3.65 to 8.65 sq ft., and c) the flue trench was wedged. Results of the study showed that the modified drier had a more uniform distribution of temperature throughout the grain bed and was more efficient (drying efficiency) than the unmodified model. Turning the grain resulted in a quicker drying.

Adeyemo (1979) made "Brook's" drier even more efficient. He determined the effect of a pyramidal cover on top of the grain bed (Fig. 3). Results showed that for a 5 feet high cover, the airflow rate was increased by 30.8 percent (6.3 to 8.24 cfm/bu), the thermal efficiency by 67 percent (21 to 35 percent). The fuel consumption was also reduced by 40 percent (1.015 to 0.610 lb wood/lb water).



Top view



Side view

FIG. 2. BROOK'S DRIER MODIFIED BY BOLDUC (1978)

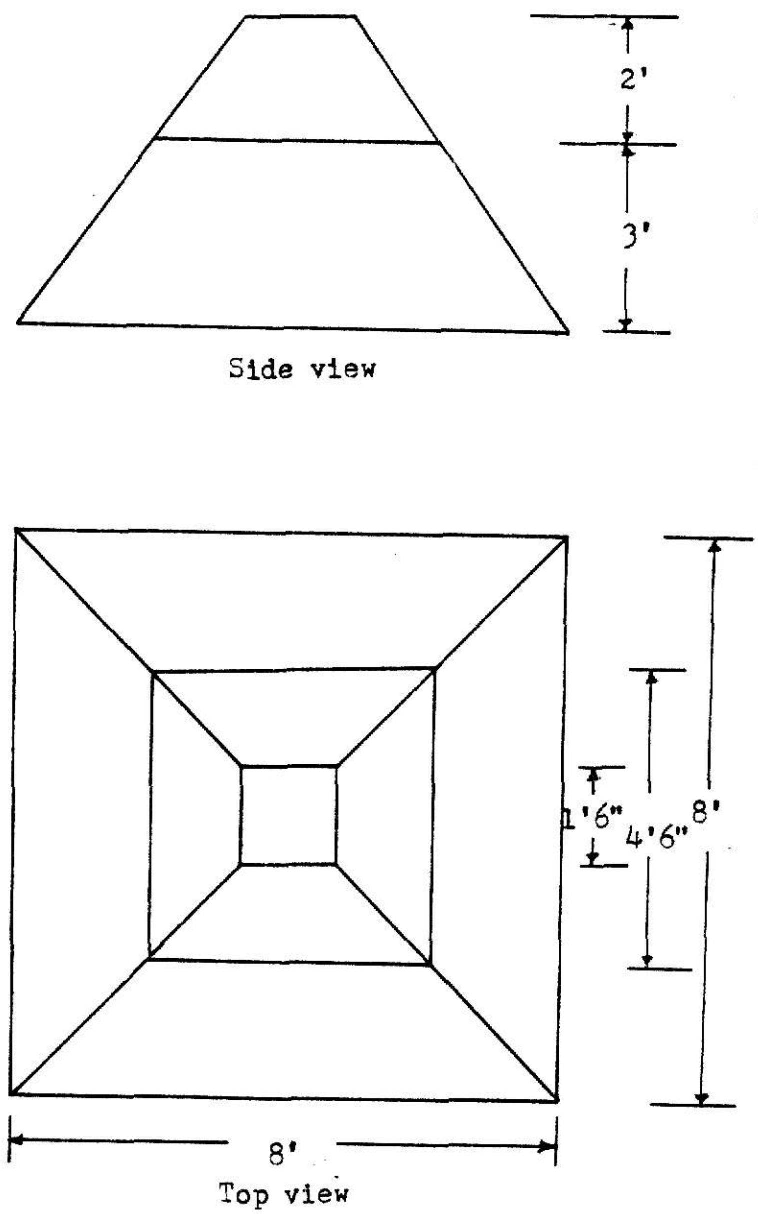


FIG. 3. PYRAMIDAL COVER USED BY ADEYEMO (1979) IN THE MODIFIED "BROOK'S" DRIER

Other designs of similar nature have also been developed. Bialostocki (1977) designed another type of drier in Nigeria utilizing wood as fuel. It differed from Brook's drier mainly in that it was constructed on the ground and used a metal diaphragm as heat exchanger (Fig. 4). The grain bed was much higher and secondary air entered through the side of the structure. In his design, indigenous materials were used except for the sheet metal elements which needed either welding equipment or pre-fabrication. The tests revealed that drying 200 kgs of shelled corn (4-inch layer) from 25 to 12 percent moisture content took only 4 hours with a firewood consumption of about 60 kgs (0.923 lb wood per lb water).

Kajewski (1977) developed a grain drier using corn residues as fuel. It was a direct-fired furnace with a 2.25 ft diameter centrifugal fan to force the air through the grain bed. During drying, the furnace was attached to a 23 ft diameter bin equipped with a perforated floor. The design of the furnace is shown in Fig. 5. He reported that the actual cost in removing 13018 lbs of moisture (6 batches of corn) was $44.93 compared to $80.26 if LP gas system was used. In conclusion, he mentioned that crop residues could provide a reliable, low-cost source of energy for grain drying. While the grain quality did not appear to be affected by this drying method, he suggested an additional quality testing to evaluate the acceptability of the corn for market.

Acasio (1972) designed a rice hull furnace for drying rough rice. The size of his furnace was about 4 cu ft (Fig. 6). He reported

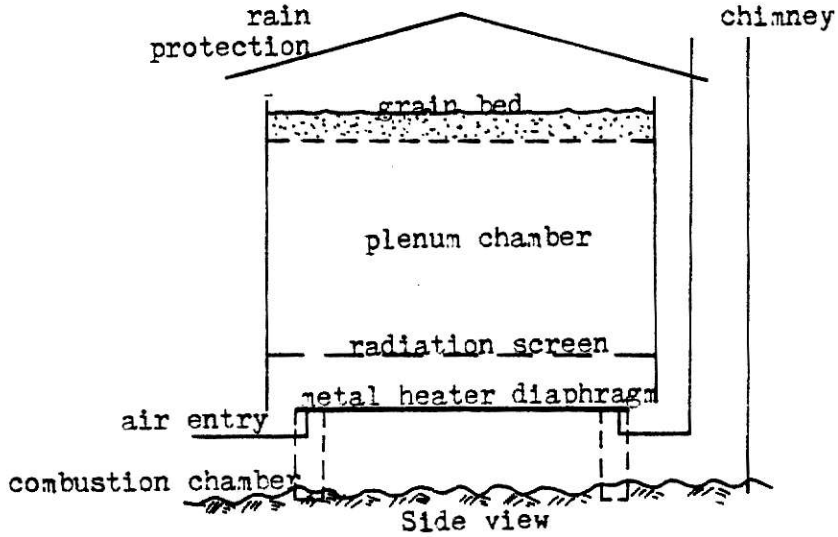


FIG. 4. BIALOSTOCKI'S DRIER (1977)

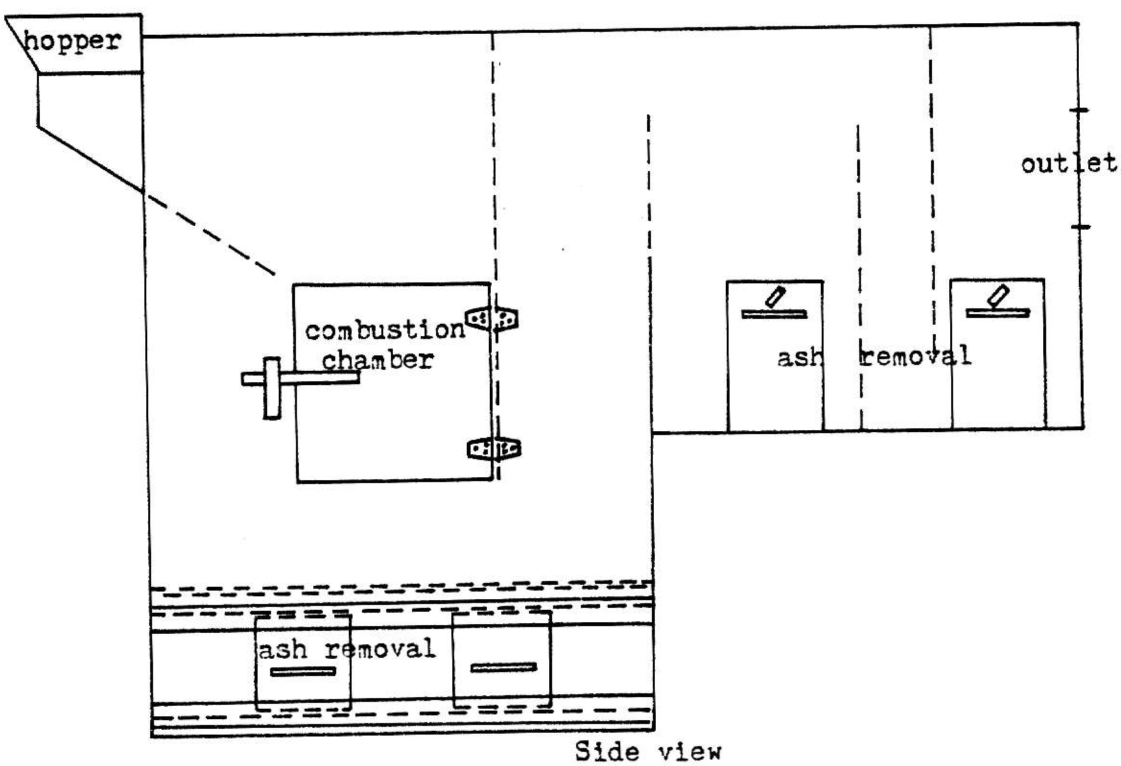
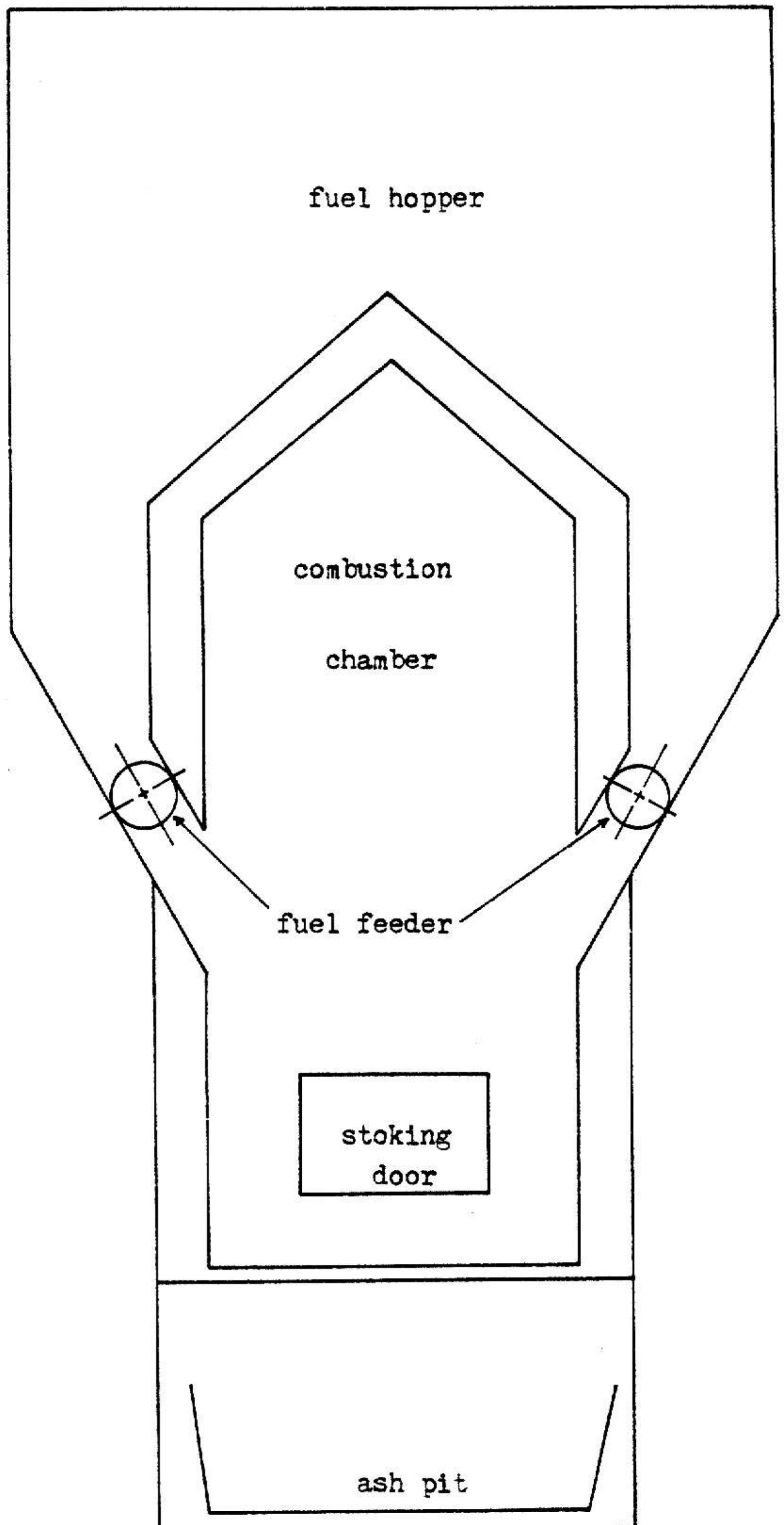


FIG. 5. KAJEWSKI'S FURNACE (1977)



Front view

FIG. 6. ACASIO'S RICE HULL FURNACE (1972)

that 9.55 lbs per hour of rice hull was the optimum rate of fuel feeding with a primary airflow rate of 45 CFM. In a 6-hr period, he dried 1144 kgs of 25 percent moisture rough rice down to 14 percent by using 110^{o}F drying air and 6' x 8' x 1½' deep grain bed. For a direct-fired rice drier furnace, Thongswang and Neubanij (1977) found that the best air to rice hull ratio was 170 kg of air to a kg of rice hulls considering that air volume was 24 times that required for combustion. No details of the furnace design, however, were presented.

Moller (1977) reported that the consumption of straw for heating a 250 sq m. house day and night was 15 to 25 bales each weighing 10 kg. Two types of straw furnaces were developed in Denmark, hopper and automatic-stoked boiler. Eckert made a comparison between the two and found that the automatic-stoked boiler had a thermal efficiency of 65 percent while that of hopper-stoked boiler had 55 percent (Moller, 1977).

Chancellor (1968, 1971) designed and tested a simple grain drier for Asia using rice straw as fuel. The principal elements of his drier were: a) a horizontal metal surface placed over a fire pit, b) the fire pit, and c) an animal to stir the shallow layer of grain on the metal surface (Fig. 7). His findings were as follows: (1) grain could be dried using heat conducted from a metal surface to supply the heat of vaporization; (2) the average rate at which moisture left the grain doubled with each 20 to 21^{o}F increase in the mean grain temperature; (3) rice when in contact with a 200^{o}F metal

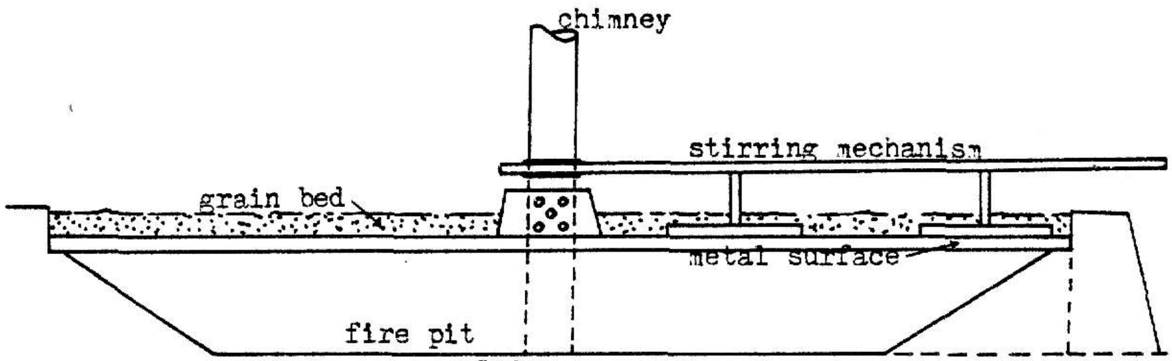


FIG. 7. CHANCELLOR'S DRIER (1971)

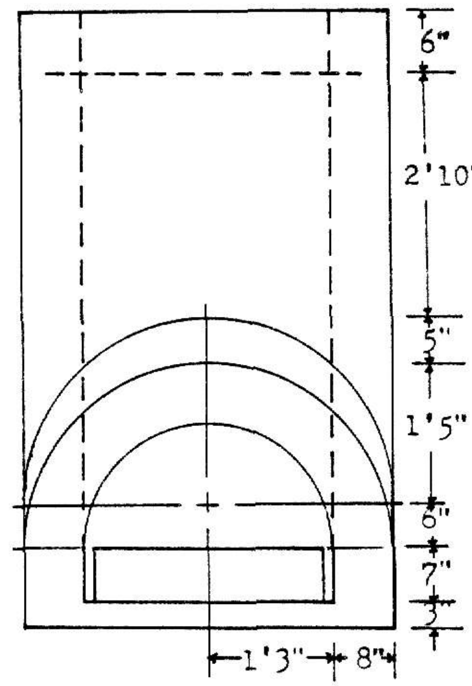
surface, had an average grain temperature of 137°F and lost moisture at a rate of 0.15 lb per sq ft per hr; (4) the fuel requirement for drying was met by the straw contained in the bundles associated with the grain to be dried; (5) grain dried by this method would not germinate and thus could not be used for seed; (6) the amount of rice-kernel breakage increased with a decrease in moisture content; (7) when milled, the rice appeared slightly yellow as compared to carefully air-dried rice, but upon cooking, no traces of yellowing were detectable; and (8) generally, rice dried at normal temperatures by this method was not distinguishable from carefully air-dried rice on the basis of taste. He also reported that the 16-ft diameter grain drier, can dry 1000 lb of rice from 24 to 14 percent moisture in 4 hours by: a) allowing the first 30 minutes of the 4-hr period to bring the grain to operating temperature; b) using 157 lb of moderately dry straw as fuel; c) using two alternating animals for stirring; d) avoiding the use of high temperatures so that milled rice is not discolored; and e) operating in humid or rainy atmospheric condition.

MATERIALS AND METHODS

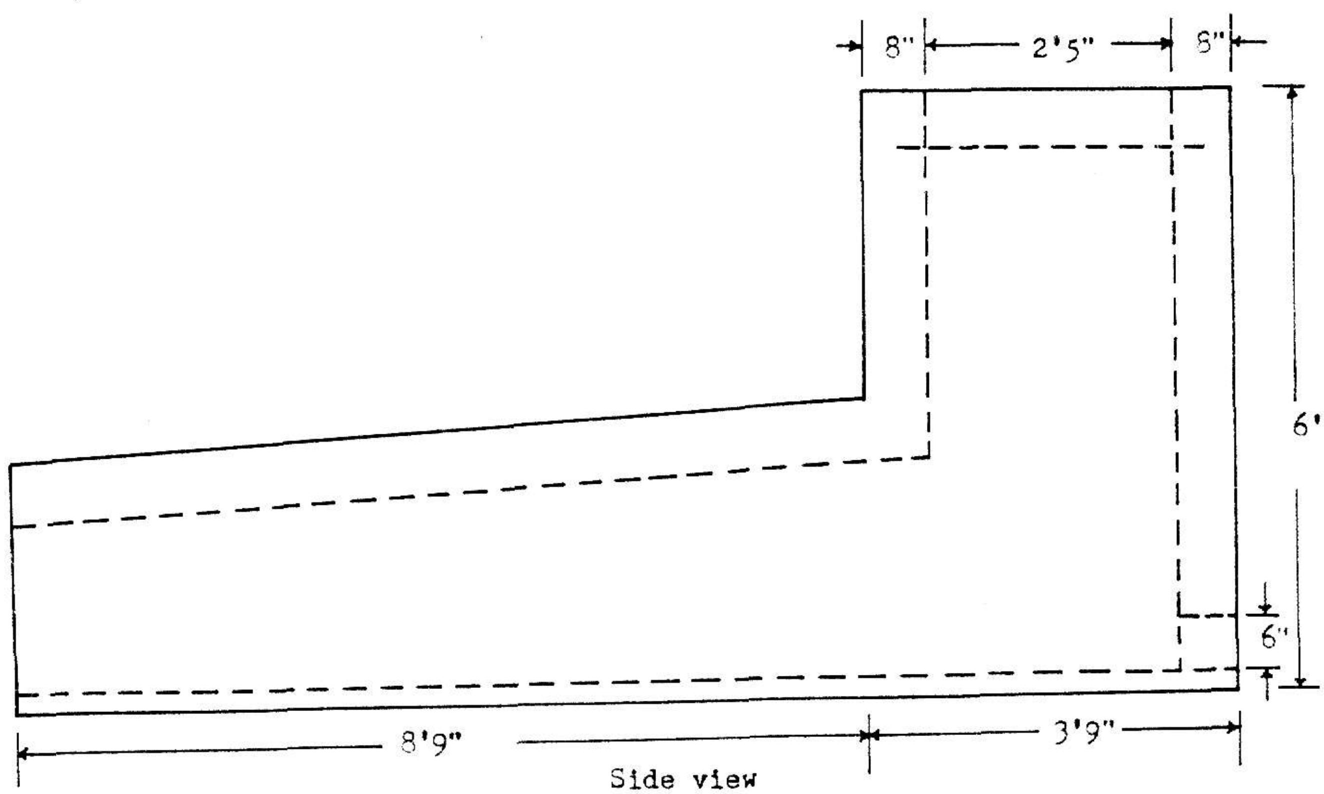
The furnace was probably the most important unit in this study. Its size and materials were considered in the construction. The selected total volume of the furnace was 33.1 cu ft (excluding the stack). A heat release rate of 7377 Btu per hr per cu ft of furnace volume was considered i.e., at a maximum fuel rate of 40 lb per hour with a heating value of 6680 Btu per lb. Since the fuel rate was a variable in this experiment, the above-mentioned heat release rate was expected to give enough flexibility in furnace operation.

A 6-ft chimney was constructed. The estimated draft by using the Sneeden and Kerr (1969) equation, $D = 353h(1/T_{air} - 1/T_{gas})$ was 0.025 in. of water. This is equal to the static pressure drop across a 12-in. deep corn bed at about 4.7 CFM per sq ft (Shedd, 1953). The anticipated draft then should give sufficient airflow through 2", 4" and 6" drying beds without difficulty.

Fig. 8 is the schematic drawings of the direct-fired drier unit while Fig's. 9 are its photographic views.



Front view



Side view

FIG. 8. DESIGN OF THE STRAW-FIRED FURNACE AND DRIER

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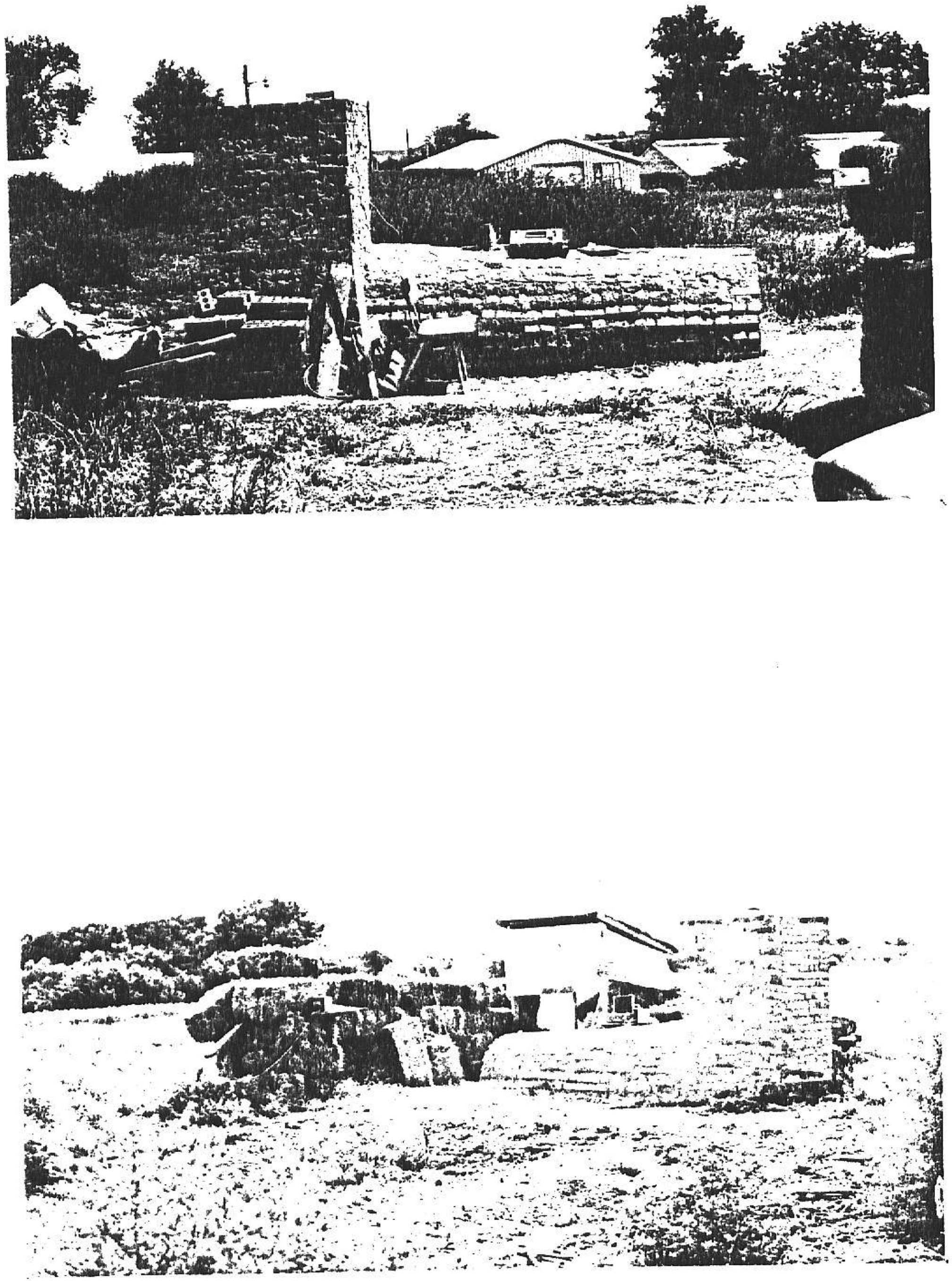

FIG. 9. PHOTOGRAPHIC VIEWS OF THE DIRECT-FIRED GRAIN DRIER

Materials. Common red bricks (3 7/8" x 4 7/8" x 7 7/8") were used in the construction of furnace and drier. This material was expected to maintain high temperature inside the furnace because of its relatively low heat conductivity which is 0.4 Btu/hr-ft^2-^{o}F-per ft (Henderson and Perry, 1976). Because of availability, ordinary bricks were favored to other low conductivity material such as fire bricks. Saturated clay was used as cementing material. It was prepared by mixing clay with sufficient water.

The furnace consisted of a semi-cylindrical tunnel with a rectangular stack underneath the drying floor. The arch shape was preferred because it is stable, structurally sound and does not need reinforcement in ordinary circumstances. A form was used to build the tunnel. The tunnel was built with a 1 in 10 upward slope to aid the flow of flue gases toward the stack. The drying floor was 3' x 3' perforated sheet metal supported by 3 angle bars (3' long) and was placed 6 inches below the top of the stack.

Loose wheat straw was used as fuel in the furnace. The weight of fuel burnt was recorded for each test using a platform scale (Fig. 12).

Instrumentation. A Thermolyne Portable Pyrometer Model PM 20700 (Fig. 10) was used to measure furnace temperatures. A thermocouple was installed under the drying floor, 8 in. from the top of the stack for the measurement of the drying air temperature. During drying, additional thermocouples were attached to the Yellow Springs Instrument Company's Tele-thermometer (Thermistor) for the measurement of grain temperature and air leaving the drier (Fig. 11).

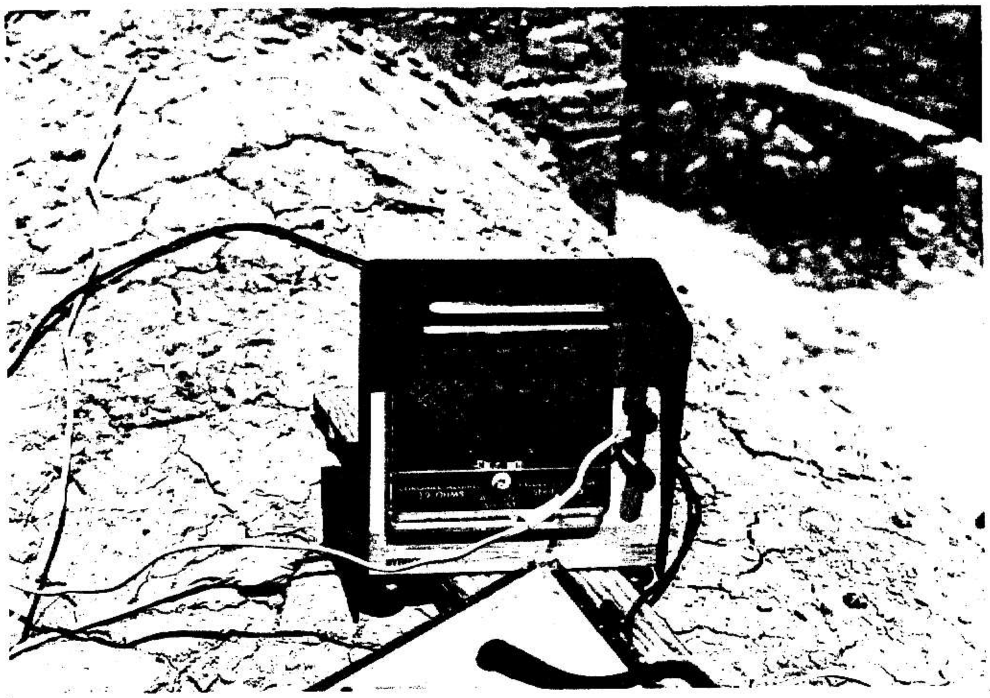

FIG. 10. THERMOLYNE PORTABLE PYROMETER
MODEL PM 20700

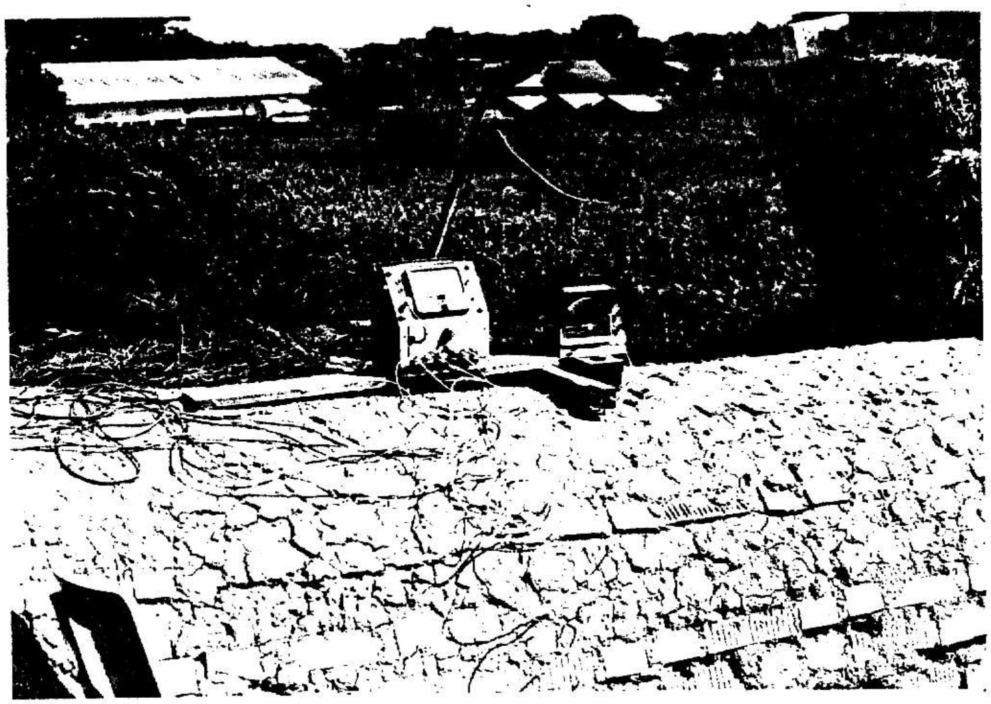

FIG. 11. YELLOW SPRINGS INSTRIMENT COMPANY'S
TELE-THERMOMETER (THERMISTOR)

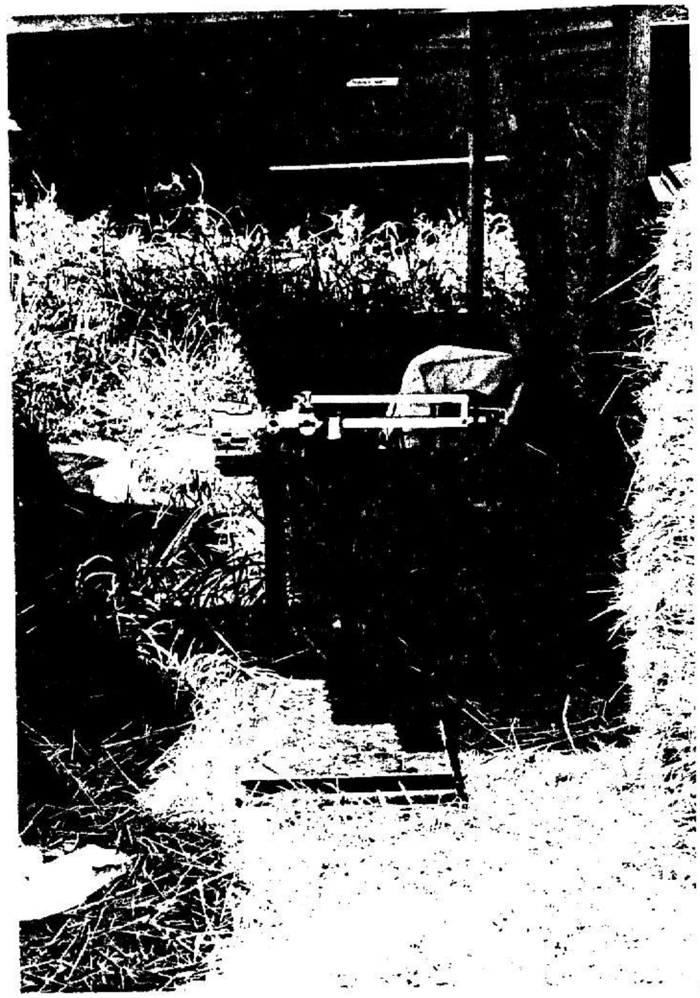

FIG. 12. PLATFORM SCALE USED TO MEASURE THE AMOUNT OF STRAW BURNT

Carbon monoxide concentration in the flue gas was determined to have an idea whether complete combustion occurred or not. The more the carbon monoxide in flue gases, the more will be the undesirable smell in grain. The determination was done by using Kitagawa Toxic gas detector kit, Model 8014-400 (Fig's. 13a & 13b).

Procedure. Three preliminary tests were conducted to determine the method and rate of fuel feeding so that drying air temperature does not exceed 130°F. In the first test, two fuel feeding rates at 20 and 40 lb per hr were used at 3 different locations in the combustion chamber (2', 4' & 6' from the air inlet). The amounts of fuel for the 20 and 40 lb per hr rates were divided into 4 batches, feeding 5 and 10 lbs, respectively every 15 minutes. The drying air temperatures were found to be higher than desired. To correct those defficiencies, continuous feeding method of fuel was used. This was considered the second preliminary test. The straw was fed gradually to keep the temperature under the drying floor as close to 130°F as possible. A small quantity of straw was fed into the furnace whenever the temperature dropped to about 120°F. Five trials were conducted and the corresponding temperature fluctuations, rates of fuel, and average drying air temperatures are shown in Fig's. A1 & A2 (Appendix). In the third preliminary test, a 4-in. layer of shelled corn was placed on the drier. Six trials were then conducted using the same procedure as in the second preliminary test. The optimum fuel rate was determined from the results of these trials which are shown in Fig's. B1 & B2 (Appendix).

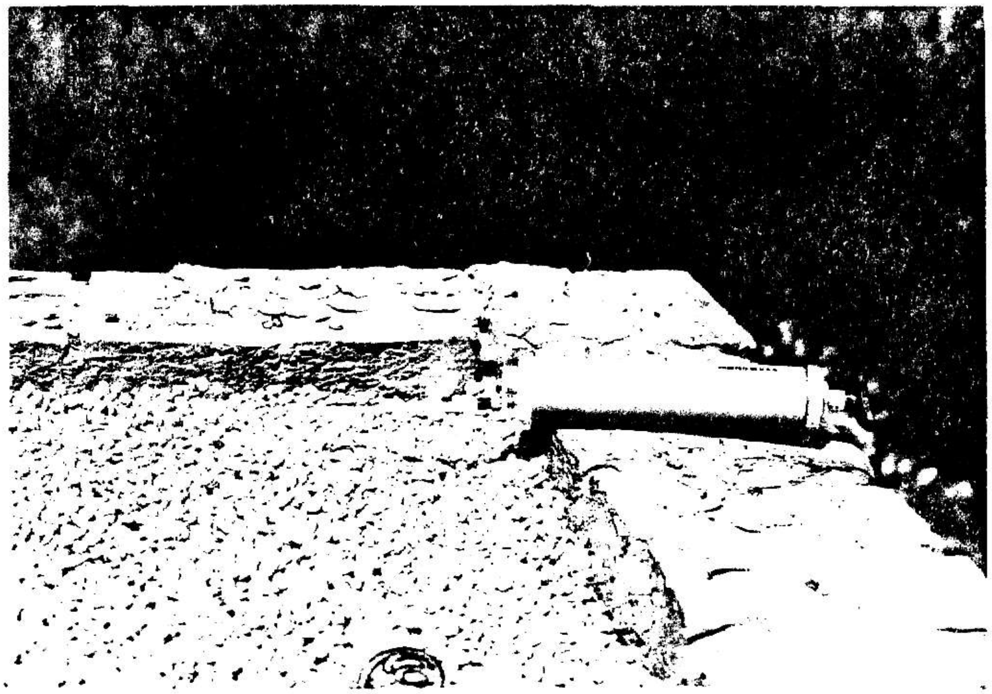

FIG. 13a. KITAGAWA TOXIC GAS DETECTOR KIT, MODEL 8014-400

FIG. 13b. MEASUREMENT OF CARBON MONOXIDE IN THE FLUE GAS BELOW THE GRAIN BED

Sixteen drying tests were conducted. Corn was dried from about 23 percent down to 14 percent moisture content (w.b.). Three independent variables were considered, namely; fuel consumption rate, grain depth and frequency of turning the grain-one level of fuel rate, 3 levels of grain depth and 3 turning frequencies (Table 1).

Due to the absence of newly-harvested corn, 25 percent moisture corn batches were reconstituted by adding water to dry grains. To assure that water was well-distributed throughout the grain mass, water was thoroughly mixed with the corn by a fine spray. The tempering drum was then rotated for about one hour and the grain was left in the drum with the lid tightly closed. It was assumed that 72 hours was sufficient to allow the water to be absorbed by the grain kernels.

Five pounds of loose wheat straw per hour was continuously fed into the furnace in each test. Temperatures of the drying air, grain, and air leaving the drier were measured at 3 different locations (Fig. 14). Temperatures at these points were taken every 30 minutes.

For moisture content determination, representative grain samples were collected from several points in the grain bed. These samples were then placed in an oven set at 103°C for 72 hours. The loss in weight was assumed to be the quantity of water evaporated from the grain samples. A dickey-john portable moisture meter was used to determine when to stop each trial. Drying was terminated when the meter registered about 14 percent moisture content (w.b.).

TABLE 1. TEST NUMBER ASSIGNED TO THE DIFFERENT TREATMENT COMBINATIONS

REPLICATION NO.	FUEL RATE LB/HR	GRAIN DEPTH IN.	FREQUENCY OF TURNING HR.	TEST NO.
1	5	2	NO TURNING	A1
			1	B1
			4	--
		4	NO TURNING	C1
			1	D1
			4	E1
		6	NO TURNING	F1
			1	G1
			4	H1
2	55	2	NO TURNING	A2
			1	B2
			4	--
		4	NO TURNING	C2
			1	D2
			4	E2
		6	NO TURNING	F2
			1	G2
			4	H2

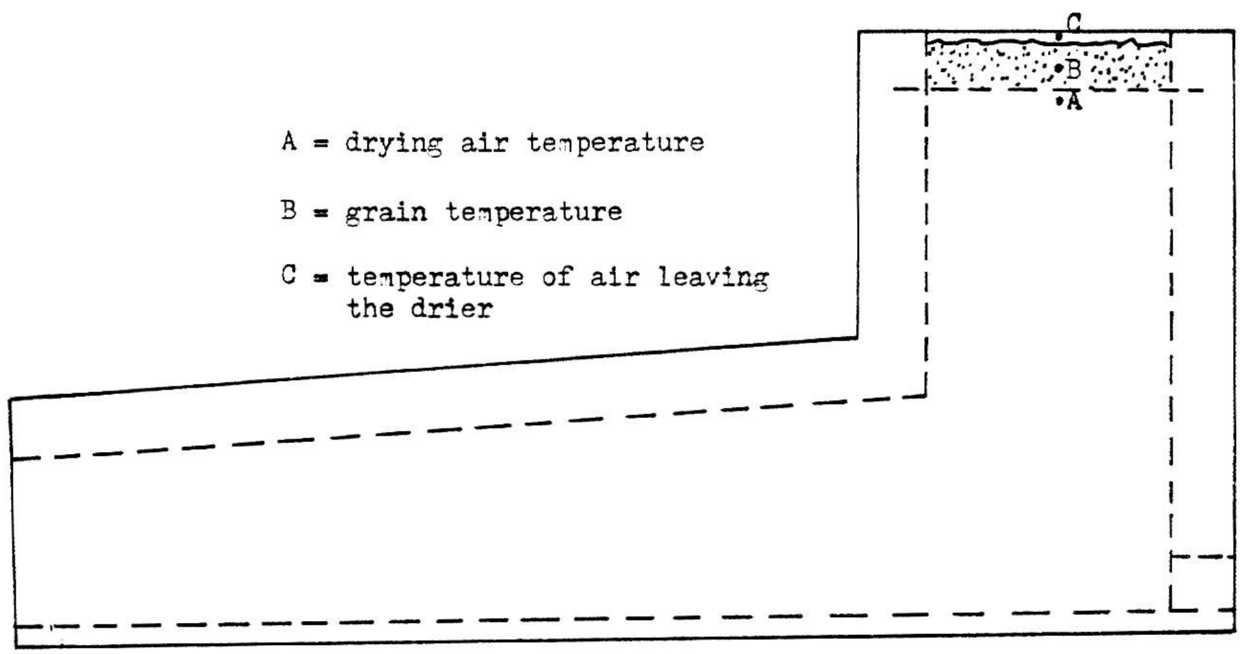

FIG. 14. POINTS OF TEMPERATURE MEASUREMENT DURING DRYING

RESULTS AND DISCUSSIONS

The first preliminary test showed that the air temperature increased when the rate of fuel was raised from 20 to 40 lb per hr and when the fuel was fed farther from the air inlet (Table 2). At 2 ft from the air inlet, it was observed that more heat escaped from the combustion chamber. By burning the fuel at the 20 and 40 lb per hr rate 6 ft from the inlet, drying air temperatures of 163.28 and 227.4°F, respectively were obtained. For all the different treatment combinations, average air temperatures were greater than 130°F and temperature fluctuations were high (Fig's. 15 and 16).

During the second preliminary test, more uniform drying air temperatures were obtained. For an average drying air temperature of 122.54 to 130.56°F, the corresponding rates of fuel were 5.75 to 6.45 lb per hr, respectively. With 8.53 lbs per hr of fuel, the air temperature was 132.16°F while the use of 28 lbs of fuel yielded an air temperature of 142.92°F. Based on these values, the optimum rate of fuel which would give 130°F approximately was estimated to be 6 lb per hr (Fig. 17).

Results of the third preliminary test showed that less fuel was needed when grains were placed on the system. With a 4-inch depth of shelled corn, the corresponding rate of fuel for 130°F drying temperature was about 5 lb per hr (Fig. 18). Heat release rate for 5 lb per hr fuel rate was estimated to be approximately 1075 Btu per hr per cu ft of furnace volume.

TABLE 2. DRYING TEMPERATURE AND CO CONTENT OF FLUE GAS IN THE FIRST PRELIMINARY TEST

FUEL RATE LB/HR	POINT OF FEEDING FROM THE AIR INLET, FT	DRYING AIR TEMPERATURE, °F			CARBON MONOXIDE (PPM)
		AVE.	MAX.	MIN.	
20	2	136.7	165	110	220
	4	149.3	180	110	226.7
	6	163.3	200	135	253.3
40	2	163.6	265	110	81.7
	4	214.7	460	105	88.3
	6	227.4	465	110	160

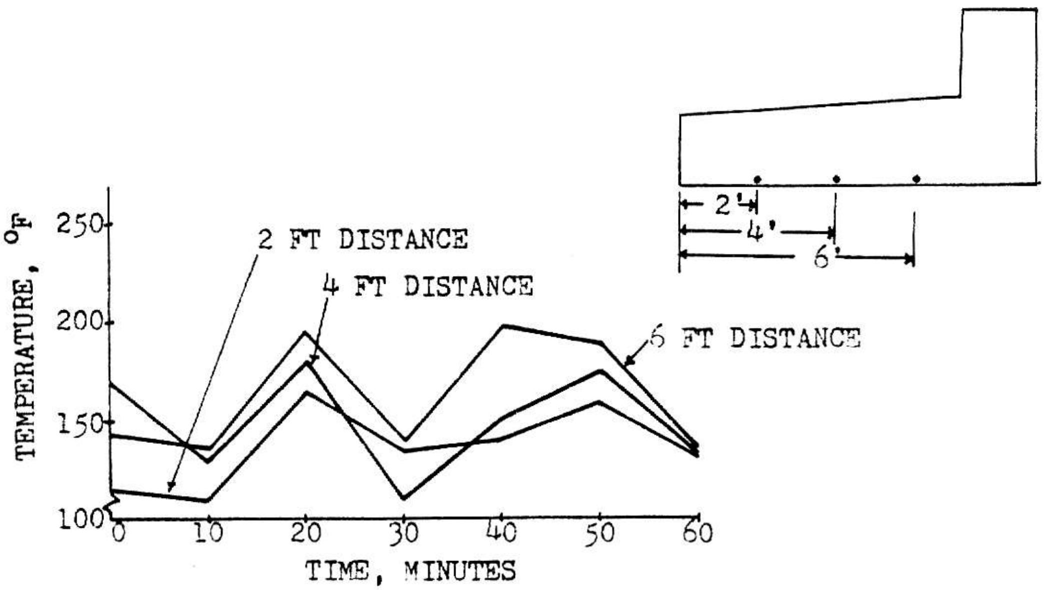

FIG. 15. DRYING AIR TEMPERATURE AT 20 LB PER HR FED AT THREE DIFFERENT LOCATIONS

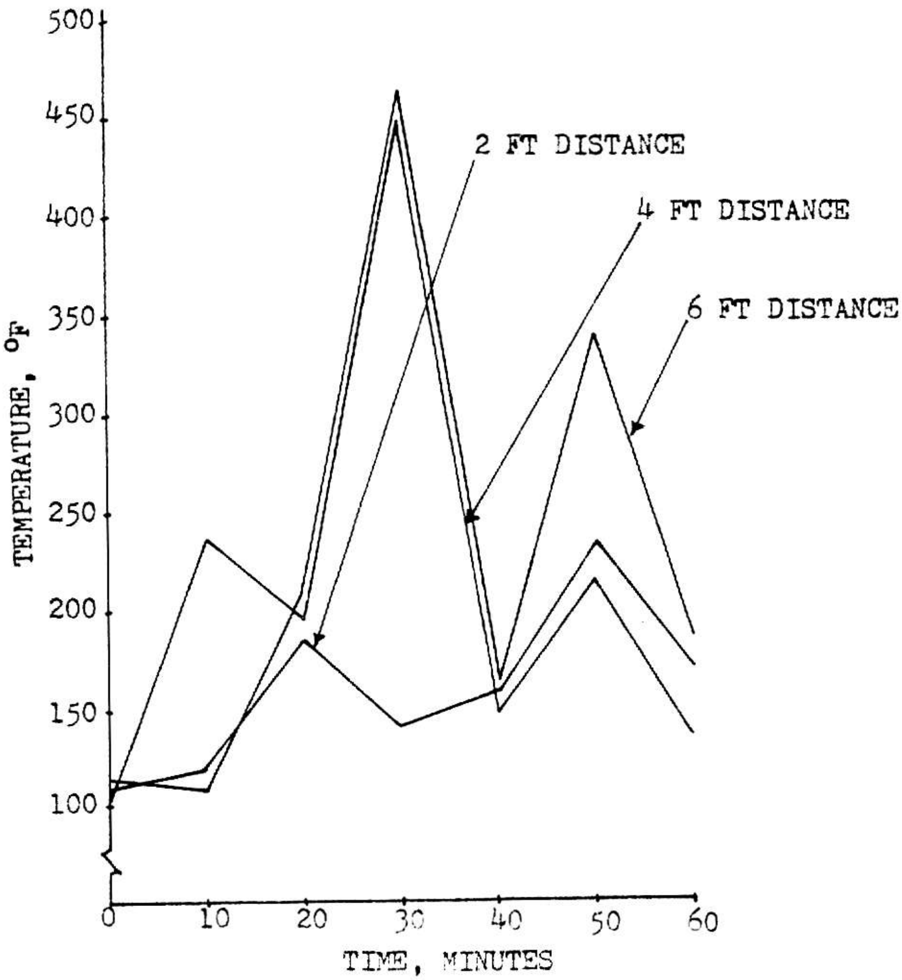

FIG. 16. DRYING AIR TEMPERATURE AT 40 LB PER HR FED AT THREE DIFFERENT LOCATIONS

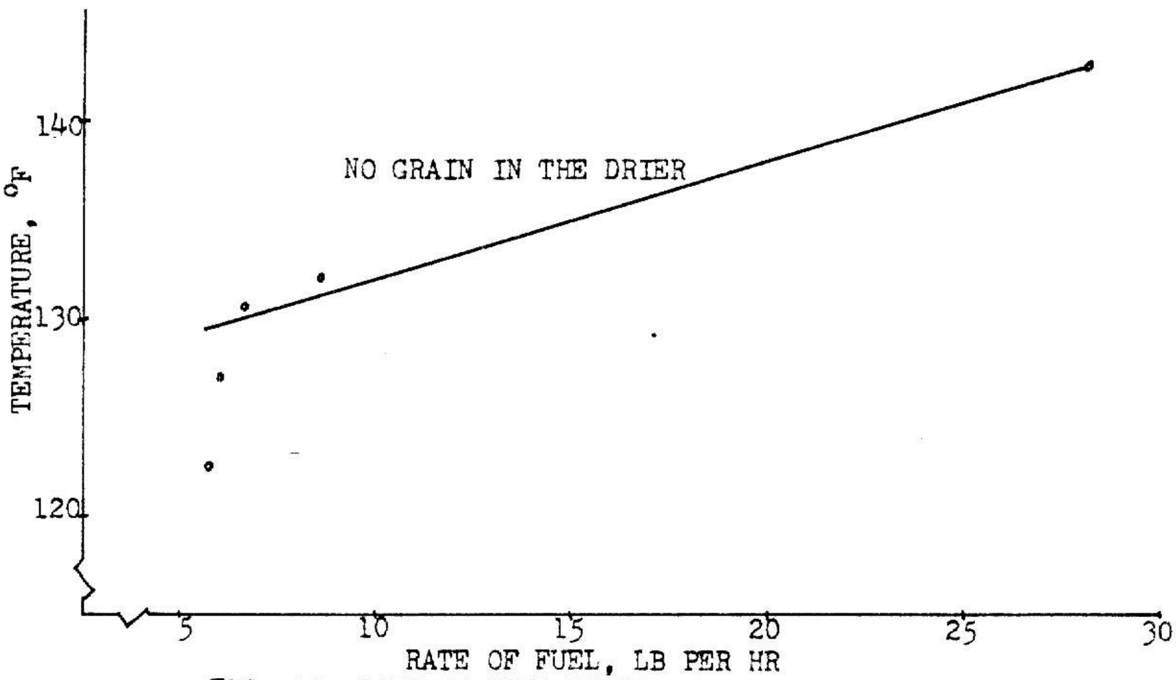

FIG. 17. RATE OF FUEL VS DRYING AIR TEMPERATURE
(SECOND PRELIMINARY TEST)

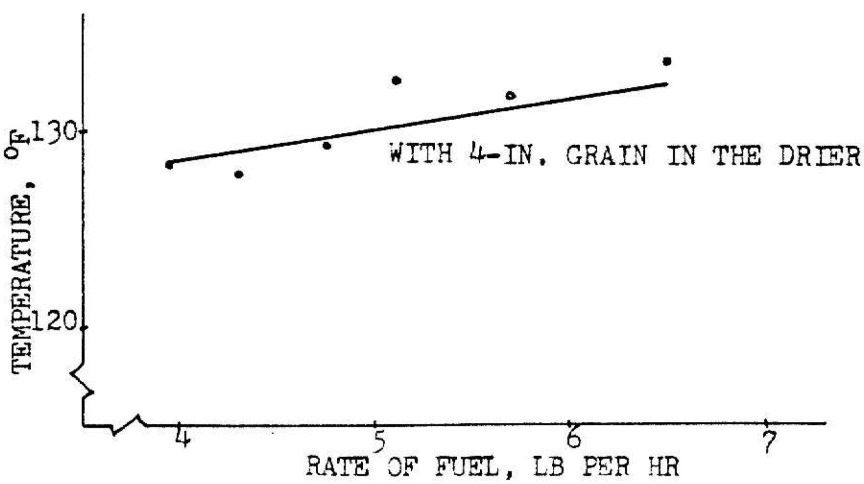

FIG. 18. RATE OF FUEL VS DRYING AIR TEMPERATURE
(THIRD PRELIMINARY TEST)

Results of all drying trials are shown in Table 3. The first column shows the test number assigned to each trial. Information such as initial and final moisture contents, drying time, hourly rate of water removed, fuel used and lb of straw per lb of water removed are also given in the same table. The amount of water in test grain was calculated by the use of the formula:

$$Wr = Wd/100(W_2 - W_1)$$

where Wr = weight of water evaporated from the grains, lb

Wd = dry matter weight in the grains, lb

W_2 = initial moisture content of the grains, %d.b.

W_1 = final moisture content of the grains, %d.b.

Results of the experiments were analyzed and the estimated drying efficiency is shown in Table 4. Drying efficiency was defined as the percent ratio of the heat used to evaporate the grain moisture to the total heat supplied. Total heat was calculated by multiplying the fuel burnt by the heating value of the fuel. Heat required to evaporate the grain moisture was calculated by multiplying the total quantity of water removed by 1500 Btu/lb, the heat required to evaporate one lb of water from corn (CAST, 1975). The drying efficiencies varied from 10.01 to 19.40 percent. The highest efficiency was for 6-in. grain depth turned every hour. The minimum drying efficiency on the other hand, was observed at 4-in. grain depth turned every 4 hours.

The quality of combustion based on the amount of carbon monoxide in the flue gas is also shown in Table 4. The extreme

TABLE 3. EXPERIMENTAL RESULTS ON DRYING RATES FOR ALL DRYING TESTS

TEST NO.	INITIAL M.C. (%)	FINAL M.C. (%)	DRYING TIME (HR)	LB H_2O REMOVED / HR	WEIGHT OF STRAW (LB)	LB STRAW PER LB H_2O
A1	23.0	14.3	2.0	2.38	10.0	2.101
A2	23.3	13.9	2.0	2.56	10.0	1.953
B1	24.1	14.5	2.0	3.02	10.0	1.656
B2	22.4	14.2	1.5	4.02	7.5	1.244
C1	24.3	16.9	6.0	2.39	30.0	2.092
C2	22.7	14.1	4.0	2.95	20.0	1.695
D1	22.5	13.9	3.0	3.88	15.0	1.287
D2	22.8	14.3	3.5	3.42	17.5	1.462
E1	22.8	13.8	4.5	2.55	22.5	1.961
E2	22.6	13.4	5.0	2.23	25.0	2.242
F1	22.7	14.3	5.5	3.28	27.5	1.524
F2	23.4	13.1	5.5	2.99	27.5	1.672
G1	22.3	13.7	4.0	4.32	20.0	1.157
G2	24.2	14.1	4.5	3.87	22.5	1.292
H1	22.9	13.9	6.0	2.90	30.0	1.724
H2	23.5	13.9	5.0	3.46	25.0	1.445

TABLE 4. ESTIMATED DRYING EFFICIENCY AND EVOLUTION OF CARBON MONOXIDE FOR ALL DRYING TESTS

TEST NO.	HEAT INPUT* BTU/HR	HEAT OUTPUT BTU/HR	DRYING EFFY** (%)	CARBON MONOXIDE (PPM)
A1	33400	3577.5	10.71	415
A2	33400	3840.0	11.50	280
B1	33400	4530.0	13.56	145
B2	33400	6030.0	18.05	210
C1	33400	3585.0	10.73	500
C2	33400	4425.0	13.25	428
D1	33400	5825.0	17.44	350
D2	33400	5130.0	15.36	481
E1	33400	3825.0	11.45	433
E2	33400	3345.0	10.01	431
F1	33400	4920.0	14.73	653
F2	33400	4485.0	13.43	656
G1	33400	6480.0	19.40	608
G2	33400	5805.0	17.38	472
H1	33400	4350.0	13.02	522
H2	33400	5190.0	15.54	680

* Heating value of wheat straw used was 6680 Btu per lb.

** Heat of vaporization of grain moisture used was 1500 Btu per lb.

values of 145 and 680 ppm were obtained at 2-in. grain depth turned every hour and at 6-in., turned every 4 hours, respectively.

Climatological data such as ambient air temperature and relative humidity were taken from the weather station. By the use of a Psychrometric chart, the drying potential of air in each trial was estimated. The difference between the water content in a unit weight of dry ambient air and that when the ambient air becomes saturated by adiabatic process was referred to as the drying potential of air. Results are presented in Table 5.

The rate of drying as affected by grain turning for each bed depth is graphically presented in Fig's. 19, 20 & 21. For the 4- and 6-in. grain depths, turning did increase the rate of drying substantially. Turning every hour resulted in the quickest drying while no turning took the longest drying time. For a 2-in. grain depth however, the drying rate was not affected by turning the grains (Fig. 19). The drying process behaved like a thin-layer drying and so turning was not necessary. In the case of 4- and 6-in. grain depths, turning distributed the moisture in bed more uniformly with respect to time and location. As a result, the drying potential of the air was more effectively used. Turning the grains increased the drying rate because of the following reasons: a) temperature gradient within the grain mass was lower; b) over-drying of a fraction of the grains was reduced; and c) grain moisture trapped above the drying zone was released. During the beginning few hours of drying process however, with 6-in. deep beds, differences in drying rate between no turning

TABLE 5. ESTIMATED DRYING POTENTIAL FOR ALL DRYING TESTS

TEST NO.	AMBIENT AIR TEMP. (°F)	AMBIENT REL. HUM. (%)	HEATED AIR TEMP. (°F)	SAT. HUM. RATIO* LB H_2O/LB DRY AIR	AMBIENT HUM. RATIO LB H_2O/LB DRY AIR**	DRYING POT.*** LB H_2O/LB DRY AIR
A1	80.88	24.38	129.6	.0183	.0055	.0128
A2	80.38	19.88	132.2	.0180	.0041	.0139
B1	79.25	36.25	131.2	.0200	.0076	.0124
B2	85.38	27.12	139.5	.0206	.0065	.0141
C1	81.38	34.00	128.6	.0200	.0078	.0122
C2	84.25	39.88	131.2	.0222	.0100	.0122
D1	87.12	33.50	133.8	.0214	.0090	.0124
D2	80.88	42.00	129.4	.0206	.0090	.0116
E1	85.50	25.62	133.9	.0192	.0063	.0129
E2	83.75	28.88	127.7	.0189	.0070	.0119
F1	69.00	25.50	131.3	.0176	.0042	.0134
F2	83.88	19.50	130.4	.0180	.0045	.0135
G1	87.62	19.25	131.6	.0185	.0050	.0135
G2	73.88	17.62	129.8	.0162	.0025	.0137
H1	79.62	50.75	130.2	.0222	.0110	.0112
H2	85.88	24.75	130.0	.0193	.0040	.0123

*Saturated air humidity ratio, lb water per lb dry air

**Ambient air humidity ratio, lb water per lb dry air

***Drying potential of the air, lb water per lb dry air

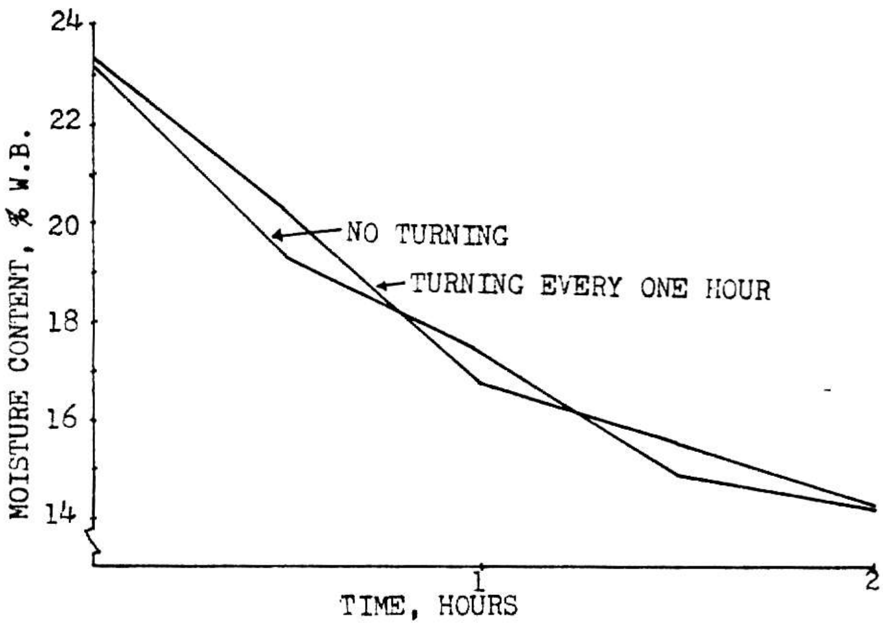

FIG. 19. RATE OF DRYING AT 2-IN. GRAIN DEPTH

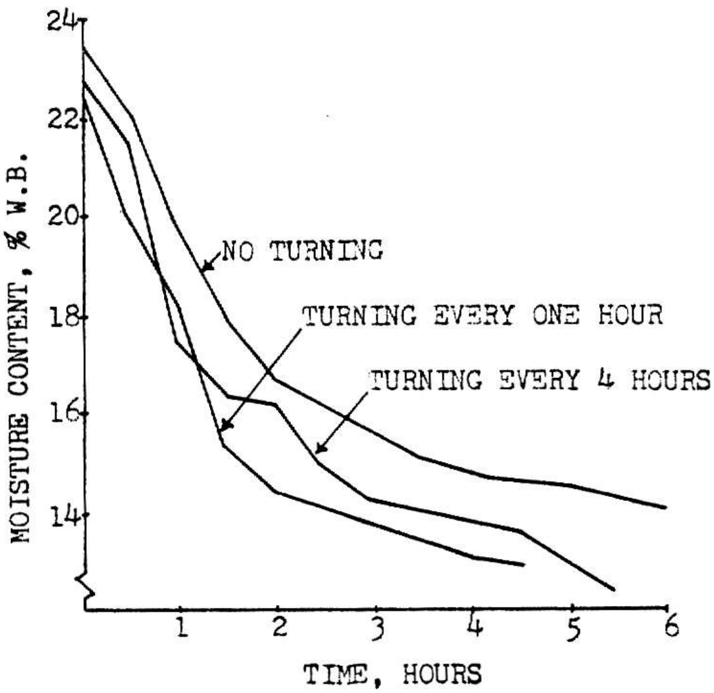

FIG. 20. RATE OF DRYING AT 4-IN. GRAIN DEPTH

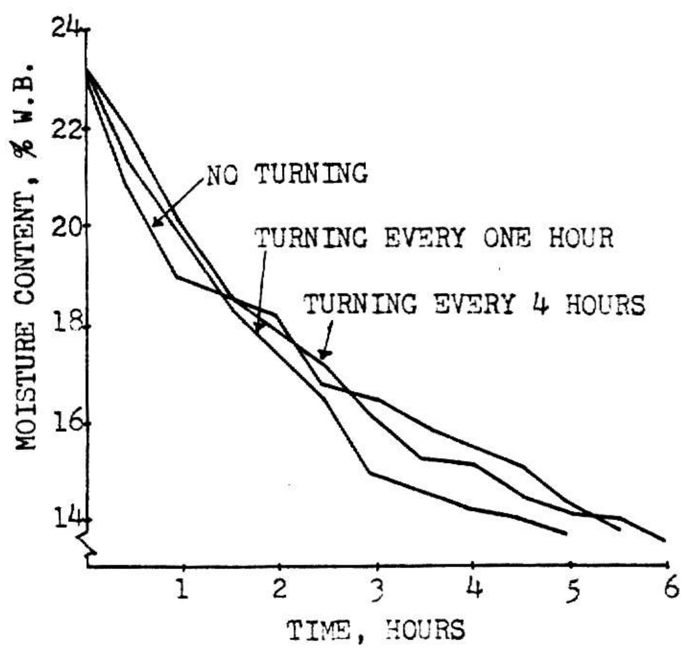

FIG. 21. RATE OF DRYING AT 6-IN. GRAIN DEPTH

and turning were insignificant (Fig. 21). The effect of turning was more prominent in the final few hours of drying. It appeared that bed depth and frequency of turning are related in some manner i.e., more frequent turning is necessary for deeper grain beds. This rule applies to deep-bed drying only.

The effect of bed depth on the rate of drying and evolution of carbon monoxide was also evaluated. For the 4-hour turning interval, 4-in. grain depth showed a higher rate of drying than 6-in. deep beds (Fig. 23). For 1 hour turning interval, 2-in. grain depth displayed the highest rate of drying, 6-in., the lowest and 4-in., in between (Fig. 24). These effects showed that the rate of drying increased when grain thickness was less. Also, the amount of carbon monoxide in the flue gas was dependent on the depth of grain; 598.5 ppm for 6-in., 437.2 ppm for 4-in. and 262.5 ppm for 2-in. grain depth (Table 6). The amount of air entering the combustion chamber was suspected to be less at higher grain depths because of greater restriction to the airflow. Consequently, it is more likely for the combustion process to be incomplete.

Table 7 shows the drying efficiency and evolution of carbon monoxide based on the frequency of grain turning. The drying efficiencies were averaged over the frequencies of turning and the highest was at one hour interval with 18.68 percent while no turning gave the least at 12.36 percent. It seems, therefore that drying efficiency could be increased by turning the grain even if the air had a lower drying potential. Evolution of carbon monoxide on the other

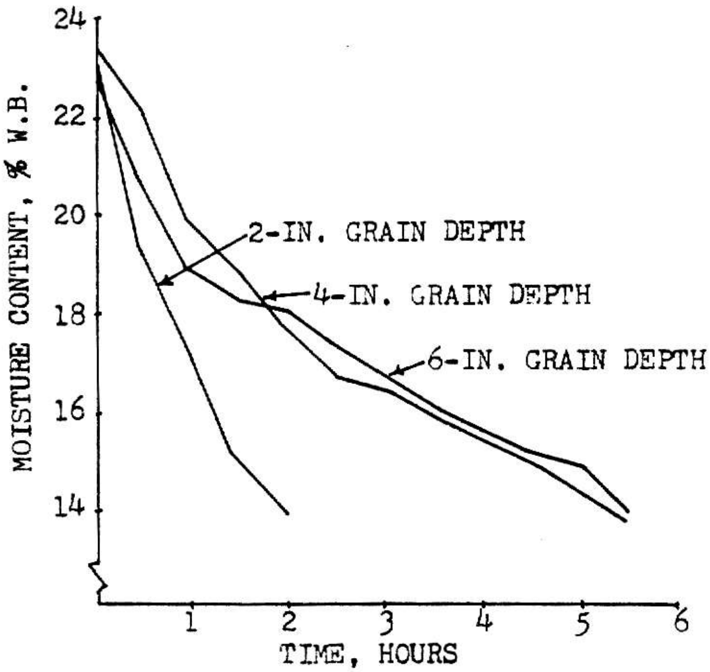

FIG. 22. RATE OF DRYING AT NO TURNING OF THE GRAIN

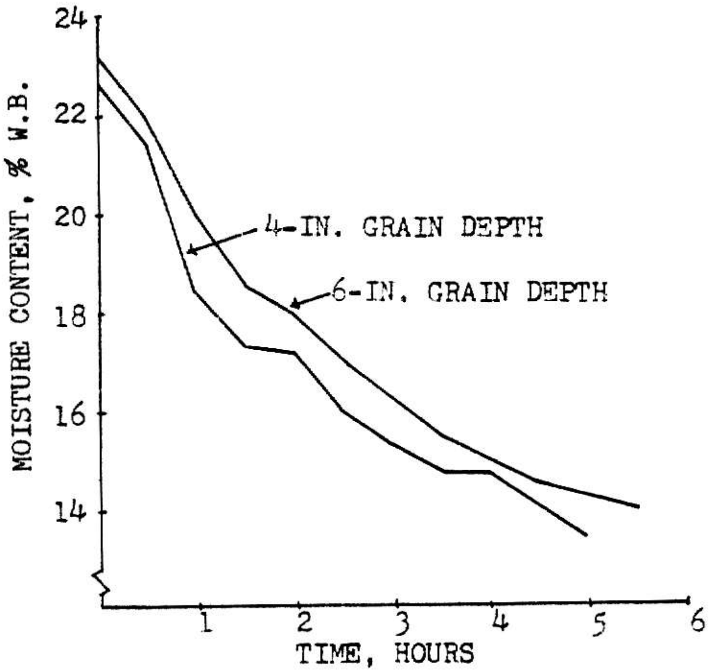

FIG. 23. RATE OF DRYING AT 4 HOURS GRAIN TURNING INTERVAL

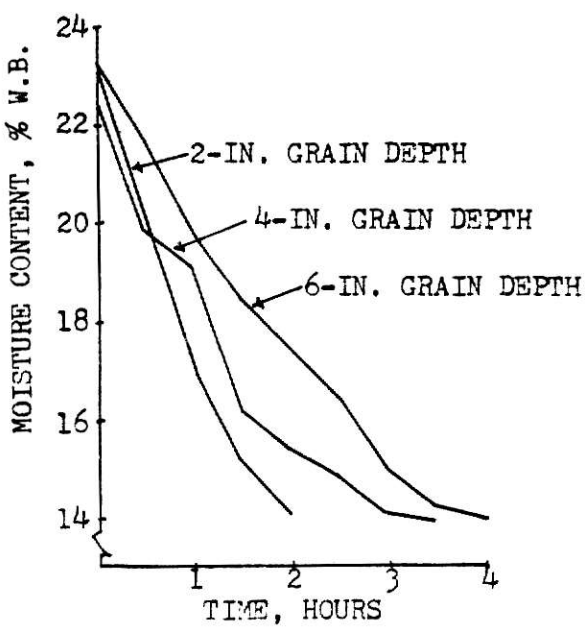

FIG. 24. RATE OF DRYING AT ONE HOUR GRAIN TURNING INTERVAL

TABLE 6. AVERAGE DRYING EFFICIENCY AND EVOLUTION OF CARBON MONOXIDE AS AFFECTED BY GRAIN DEPTH

GRAIN DEPTH (IN)	DRYING EFFY. (%)	CARBON MONOXIDE (PPM)	DR. POT. LB H_2O PER LB DRY AIR
2	13.45	262.5	.0133
4	13.04	437.2	.0122
6	15.58	598.5	.0129

TABLE 7. AVERAGE DRYING EFFICIENCY AND EVOLUTION OF CARBON MONOXIDE AS AFFECTED BY TURNING THE GRAINS

FREQUENCY OF TURNING (HR)	DRYING EFFY. (%)	CARBON MONOXIDE (PPM)	DR. POT. LB H_2O PER LB DRY AIR
NO TURNING	12.36	488.67	.0130
1	16.86	377.67	.0130
4	12.50	460.17	.0120

hand, was less when the grain was turned more frequently.

Drying efficiencies and specific fuel consumptions expressed in lb of fuel required to evaporate one lb of water from the grain for driers used by Bolduc (1978), Adeyemo (1979) and in this study are shown in Table 8. The modified Brook's drier with a 5-ft cover had the highest drying capacity of 12.94 lb water per hr and drying efficiency of 28.32 percent. In addition, the fuel consumption rate was 0.746 lb wood per lb of water. The corresponding figures for this study were 2.39 lb water per hr, 10.59 percent and 2.100 lb straw per lb of water. The lower drying efficiency and high fuel consumption rate of the direct-fired drier used in this study could be due to the following: (1) slower rate of drying; (2) loss of heat from the combustion chamber through the air inlet; (3) relatively smaller grain bed; and (4) a lower heating value of wheat straw compared to wood.

Adeyemo (1979) found that a 4-in. grain depth turned every 6 hours was the most efficient variable combination for the modified Brook's drier with a 5-ft pyramidal cover. He reported a specific fuel consumption rate of 0.610 lb wood per lb water (35 percent drying efficiency) for the above-mentioned drying situation. In this experiment, the best drying performance was observed at 6-in. grain depth turned every hour which gave 1.221 lb straw per lb water (18.38 percent drying efficiency). The big difference in the drying performance of the two driers may be attributed to the difference in the size of the drying bed (6.25 vs 64 ft^2). Bigger drying floor area is

TABLE 8. DRYING CAPACITY, DRYING EFFICIENCY AND SPECIFIC FUEL CONSUMPTION OF THREE TYPES OF DRIERS AT 4-IN. GRAIN DEPTH TURNED EVERY 4 HR.

TYPE OF DRIER	LB H_2O REMOVED / HR	DRYING EFFY. (%)	LB FUEL PER LB H_2O
MODIFIED BROOK'S DRIER (BOLDUC, 1978)	6.03*	13.26*	1.593*
MODIFIED BROOK'S DRIER WITH A 5-FT PYRAMIDAL COVER (ADEYEMO, 1979)	12.94*	28.32*	0.746*
DIRECT-FIRED DRIER USING STRAW AS FUEL	2.39**	10.59**	2.100**

*Based on the average of 25 and 20 percent initial moisture content of grains (w.b.)

**The initial moisture content of the grains was 22.7 percent (w.b.)

expected to give higher drying capacity, drying efficiency and better combustion due to an increase in the amount of grain per batch and a bigger room for the flue gases under the grain bed.

Finally, since straw provided enough heat in drying shelled corn to a maximum depth of 6 inches, it seems to be a viable source of fuel for grain driers. On the other hand, lower rates of drying and drying efficiencies were noted in using the direct-fired grain drier compared to Brook's drier. It is therefore suggested that the following factors be considered for future studies on direct-fired grain driers using straw as fuel: (1) better insulation; (2) higher slope of the combustion chamber leading to the stack; (3) bigger drying floor area; (4) use of grate for proper mixing of fuel and air during combustion; (5) higher chimney; and (6) evaluation of the quality of dried grains (both appearance and taste) for economic purposes.

CONCLUSIONS AND RECOMMENDATIONS

For a direct-fired grain drier using wheat straw as fuel, the following conclusions were made:

a) drying grain using wheat straw as fuel is a viable method of grain drying;

b) a heat release rate of 1075 Btu per hour per cu ft of furnace volume was estimated to be satisfactory for a direct-fired furnace;

c) continuous feeding of the fuel is recommended for a minimum fluctuation of the drying air temperature;

d) the optimum fuel feeding rate for an air temperature of 130°F was found to be 5 lb per hour for 2", 4" and 6" grain depths;

e) turning the grain every hour compared to no turning and turning every 4 hours resulted in highest drying efficiencies;

f) a 6-in. grain depth is suggested as the optimum grain depth for this system because of its high drying efficiency over the rest of the treatments;

g) under actual drying situations, the direct-fired drier used in this study could not be recommended over the modified Brook's drier unless modifications are made to improve its drying performance; and

h) finally, it is suggested that further investigations for grain drying using a direct-fired furnace be conducted taking the following factors into considerations;

   (1) the slope of the combustion chamber leading to the chimney should be increased;

   (2) heat loss from the combustion chamber must be minimized (better insulation and design);

(3) fuel burning should be on an elevated grate;

(4) more importantly, the size of the drying bed and the height of the chimney should be increased; and

(5) the quality of dried grains both on the basis of appearance and taste must be evaluated for economic purposes.

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A P P E N D I X

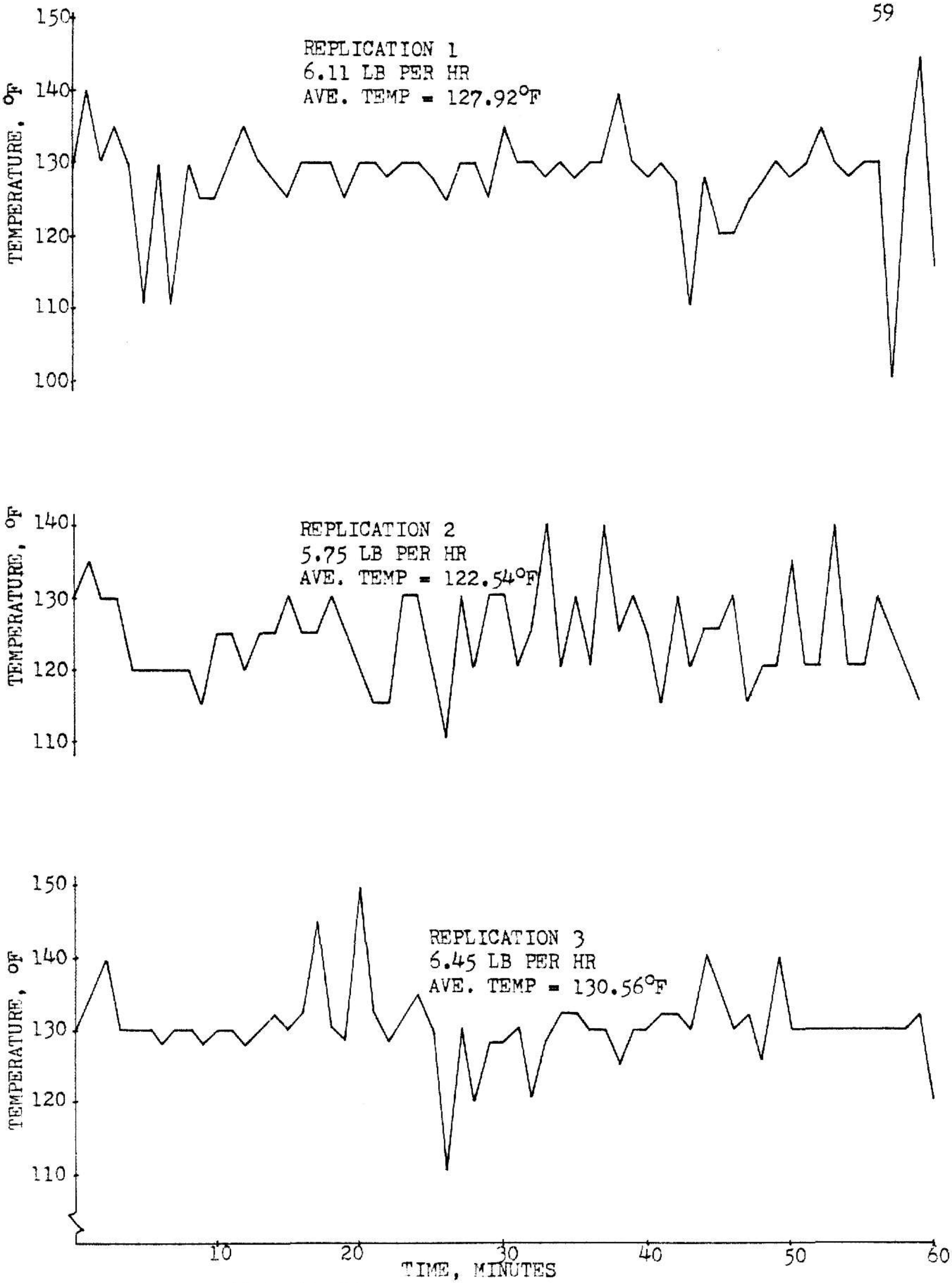

FIG. A1. DRYING AIR TEMPERATURE FLUCTUATIONS
(SECOND PRELIMINARY TEST)

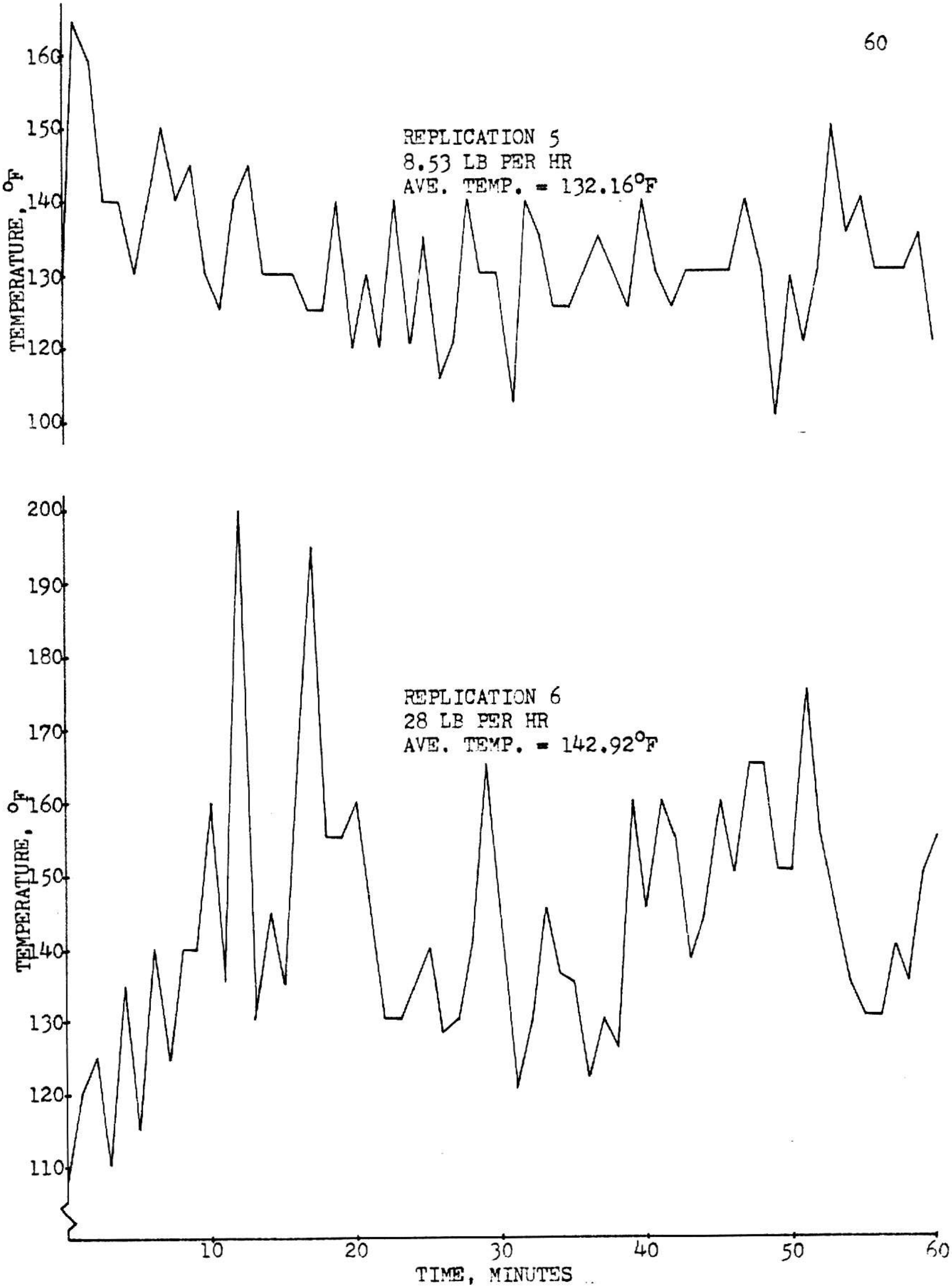

FIG. A2. DRYING AIR TEMPERATURE FLUCTUATIONS
(SECOND PRELIMINARY TEST)

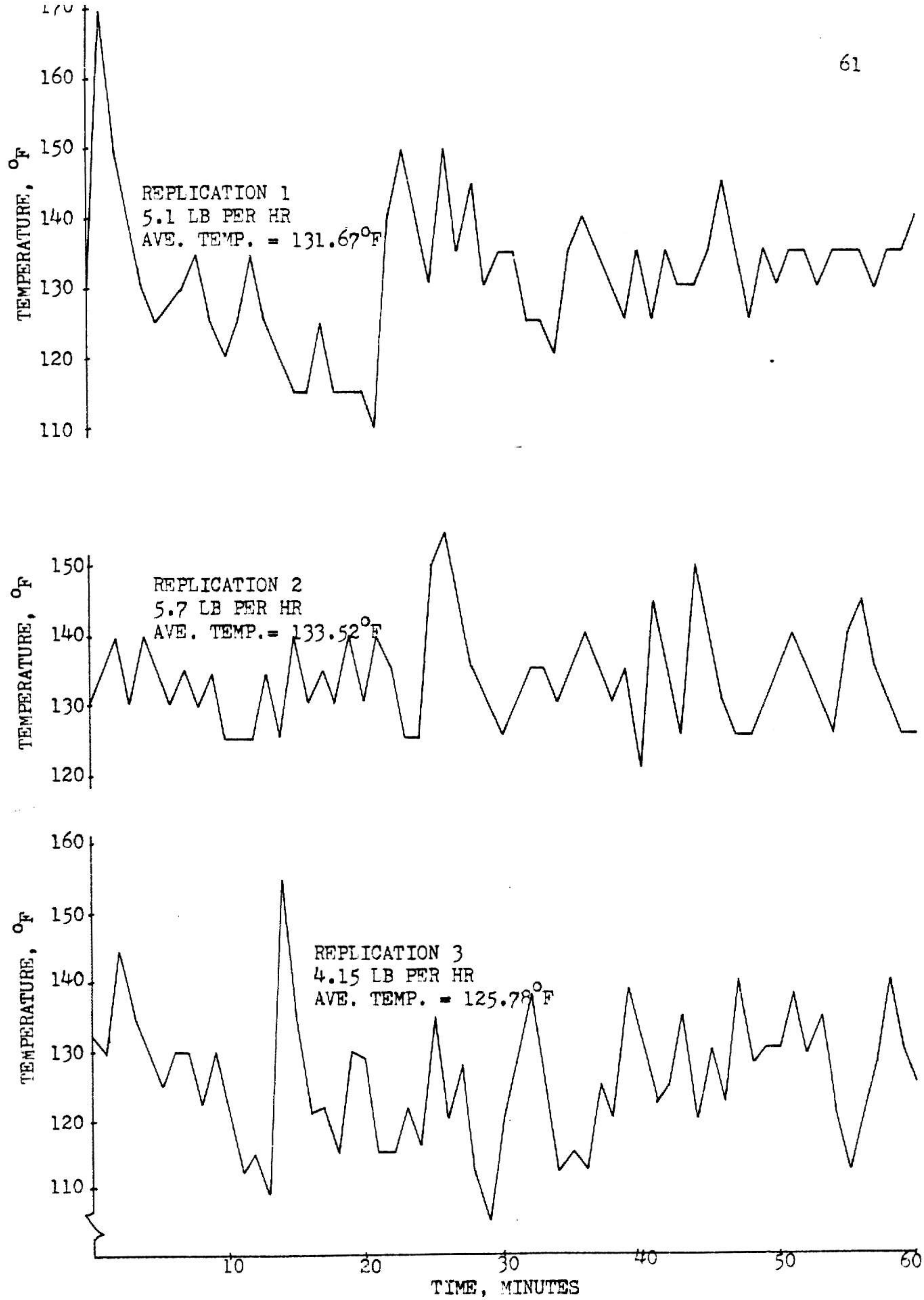

FIG. B1. DRYING AIR TEMPERATURE FLUCTUATIONS
(THIRD PRELIMINARY TEST)

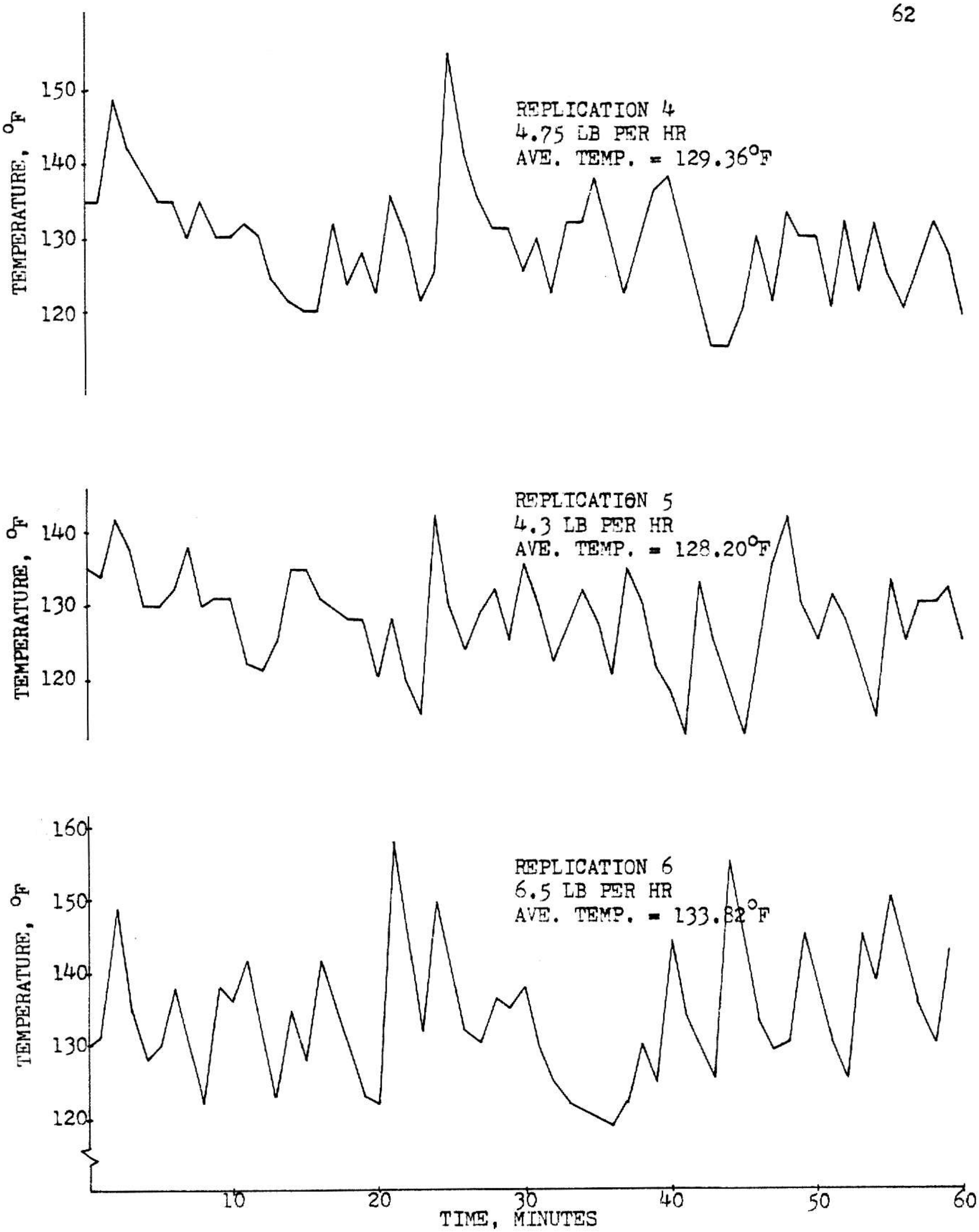

FIG. B2. DRYING AIR TEMPERATURE FLUCTUATIONS
(THIRD PRELIMINARY TEST)

STRAW-FIRED FURNACE FOR GRAIN DRYING PURPOSES

I. TOOLS AND MATERIALS

a) 3 7/8" x 4 7/8" x 7 7/8" ordinary red bricks

b) perforated sheet metal for the drying floor

c) 2" x 2" x 10' lumber

d) 2" x 2" x 1/8" angle bars

e) 4' x 8' galvanized iron sheet metal

f) 1½ G.I. nails

g) ½" thick plywood

h) clay (Kaolinite)

i) plentiful source of water

j) construction tools such as saw, hammer, trowel, etc.

II. MANPOWER (1 working day = 8 hours)

a) cleaning and leveling of the site .... 2 days

b) preparation of the form .... 1 "

c) construction of the furnace and drier ....7-10 "

d) installation of the drying floor ....1 "

Total ... 11-14 days

III. PROCEDURE FOR CONSTRUCTION

a) select a well-draned site that is far from buildings or piles of straw or wood,

b) air inlet must be positioned to the direction of the wind for maximum supply of air during burning,

c) the cementing material (clay) must be thoroughly saturated and mixed with water before using,

d) be sure that the cementing material (clay) is pressed (compacted) in-between the bricks during construction for minimum crack formation during the curing and/or drying period,

e) a window must be provided below the stack for the removal of ashes and unburnt fuel, and

f) finally, the supports (angle bars) and the drying floor (perforated sheet metal) must be properly installed.

A STRAW-FIRED FURNACE FOR GRAIN DRYING PURPOSES

by

APOLONIO VALENTINO GUEVARRA

B.S.A.E., CLSU, PHILIPPINES, 1975

AN ABSTRACT OF A MASTER'S THESIS

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requirements for the degree

MASTER OF SCIENCE

Department of Grain Science & Industry

KANSAS STATE UNIVERSITY
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ABSTRACT

The main objective of this study was to design and construct a direct-fired drier using loose wheat straw as fuel. Factors such as drying potential of the heated air, drying capacity, drying efficiency and quality of flue gas (evolution of carbon monoxide) were considered using different grain depths and frequencies of grain turning.

The furnace and drier were constructed using common red bricks (3 7/8" x 4 7/8" x 7 7/8") in favor of other materials because of its low heat conductivity, low price and availability. Clay was used as the cementing material for the bricks. For the drying floor area, a perforated sheet metal supported by angle bars was used.

Three preliminary tests were conducted to determine the rate of fuel feeding which will give a drying air temperature of about 130°F with minimum fluctuation. Results showed that with a 4-in. grain depth in the drier, continuous hand-feeding of loose wheat straw at 5 lb per hour was satisfactory. This gave a heat release rate of about 1075 Btu per hr per cu ft of furnace volume.

Sixteen drying trials using shelled corn at about 23 percent moisture content dried to about 14 percent (w.b.) were conducted to determine the drying performance of the furnace-drier unit. For the different grain depths used, grain turning did increase the drying rate except for 2-in. which was not affected. However, for 6-in. grain depth, turning was observed to be more prominent in the final few hours of drying than at the beginning of the drying process.

The highest drying efficiency of 18.38 percent (1.221 lb straw per lb water) was obtained at 6-in. grain depth turned every hour. On the other hand, the rate of drying in terms of lb of water evaporated per hr was highest at 2-in. grain depth followed by 4- and 6-in. in a decreasing order. The quality of the flue gas (evolution of carbon monoxide) was observed to be less for thinner grain beds and at more frequent grain turning.

It was also found out that the rates of drying and drying efficiencies obtained from this experiment were much lower than the modified Brook's drier. It could be attributed to the loss of heat from the combustion chamber through the air inlet due to the big difference in the grain bed area of the two driers (6.25 vs 64 ft^2). Also, to some extent, the difference in the heating values of the two types of fuel (6680 Btu/lb for wheat straw and 7100 Btu/lb for wood).

Due to the lower drying efficiency of the system used in this experiment though directly fired, the following recommendations were deemed necessary: (a) the slope of the combustion chamber leading to the chimney must be increased; (b) the design of the furnace-drier unit must be improved for better insulation; (c) grate must be used for better combustion; (d) the height of the chimney and the size of the grain bed must be increased; and (e) the quality of dried grain (both color and taste) must be evaluated for economic purposes.