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Solar Grain Drying Conference Proceedings

May 2-3, 1978

Holiday Inn-North
West Lafayette, Indiana

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Edited by James G. Hartsock
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SOLAR ENERGY FOR GRAIN DRYING

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Some background and history of research and development activities in solar grain drying should be helpful in putting current research efforts into perspective. Tests were started at seven locations in the fall of 1974, following the oil crisis of 1973. Research was continued in 1975 with 13 participants and in 1976 with 15 participants. Now, in the fourth year of the research program, there are 12 participants that will be reporting to this conference.

Solar grain drying is not a recent innovation. As pointed out in a review by the authors (Foster and Peart, 1976), solar grain drying research has been in progress since the 1950's. Although established as technically feasible at an early date, it was not cost competitive with plentiful and low cost petroleum fuel.

Most of the research effort has been directed toward applying solar energy to low-temperature, in-storage grain drying systems. Collecting sun energy to supplement the heat in natural air used for in-storage drying appears logical upon examination of the principal attributes of solar energy.

CHARACTERISTICS OF SOLAR ENERGY

The following characteristics of solar energy bear on its use for solar grain drying.
(1) Solar energy is diffuse, low-grade energy, easily applied to low temperature applications.
(2) It is an intermittent source of energy available only in the daytime in clear weather.
(3) It is a capital intensive source of energy with high fixed cost and low variable or operating cost.
(4) It is ubiquitous, and except for geographical variation, and occasionally, local interference, is equally available to all at the point of use.

How do solar grain drying requirements mesh with the characteristics of solar energy? Well and not so well.
(1) Grain drying is easily adapted to use solar energy, as large volumes of low temperature air are used. Air entering a solar collector is usually at ambient temperature and for in-storage drying systems is heated only a few degrees. In contrast, the air entering collectors for shelter heating is at the minimum comfort level for the occupants, normally several degrees above ambient temperatures during the cold part of the year. Since the heat losses from the collector are proportional to the difference between ambient and the average collector temperature, it is obvious that heat losses from the collector used in grain drying would be low. Thus, relatively low cost collectors are effective for in-storage grain drying.

(2) In-storage grain drying proceeds for several days and is subject to variations in the drying potential of the ambient air. Solar energy, available only during daylight hours, adds to the variation of drying potential between day and night. Fortunately, low temperature drying systems can tolerate such variable levels of heat input. The grain stores excess energy in the form of overdried grain. The overdried grain then acts as a desiccant and removes excess moisture from high humidity night air so drying can proceed. So the grain, in effect, provides its own storage for solar energy.

Several approaches to storing solar heat - or drying potential - other than in grain, are being studied. Although probably required for higher speed, higher temperature drying systems, the need for external thermal storage for low temperature bin drying systems has not been fully established.

(3) The capital intensiveness of solar energy presents a problem in its application to grain drying. Corn requires more drying energy than other grains. Corn is dried in the fall during a relatively short period of 6-8 weeks. The annual utilization of solar equipment for corn drying alone is too low for cost effectiveness. For example, different analyses (Meinel and Meinel, 1977; Williams et al. 1977) show that at present prices, the fuel saving affected by the solar heat collected would justify an investment in collectors of less than \$1 per ft^2. Costs at this low level are possible only with very simple plastic collectors, and these would need to be stored and protected when not in use to prolong their life. The estimated life of the collector, along with its first cost and the volume of grain dried, were the three factors contributing most to the cost effectiveness of solar drying systems (Heid, 1978).

(4) The ubiquitous nature of solar energy permits collection and use at the point or points of greatest need and convenience. There is little economy of scale in the collection and use of solar energy.

Economic and systems analyses are being emphasized in current research efforts. One of the critical questions is that of multiple use. Multiple use of the same equipment increases annual use and amount of energy collected per dollar of investment. But multiple use collection systems cost more, especially if they meet requirements for shelter heating. Compared to a collector used solely for grain drying, a multiple use collector will operate at a higher temperature and either will have greater losses or will require added expense for double or triple glazing, and for backside insulation. Some type of thermal storage will be required if comfort heating is involved. There is also competition for the energy available from competing or conflicting multiple uses and the collectors may need to be portable. However, opportunities to use the same solar equipment do do more than one job should not be overlooked, and there are some interesting approaches being studied and proposed for study.

Utilization of the collector for more than one grain crop is another multiple-use arrangement that needs more study. Wheat drying with solar energy has been shown (Barrett, 1978) to allow harvest 1 to 2 weeks early, permitting earlier soybean planting following wheat and improving chances for a good soybean yield. This double-cropping practice has been growing rapidly and provides interesting possibilities of solar drying of wheat and corn in the same bin, wheat in June and July and corn in October and November.

Another multiple use aspect that needs more study is the incorporation of a solar collector into a building sidewall or roof. This has been shown to be feasible on grain bin walls and machinery and livestock building walls and roofs, with the solar heat used both for grain drying and for space heating.

Much has been learned in the four years that the current federally sponsored research program has been in existence. We have tried a number of approaches; some worked well, some not so well. But now, we have data on performance and on costs from which more definitive economic studies can proceed.

Farmer interest has been increasing during the four-year period and the program has been well publicized in the agricultural press. Many solar installations in use today were not purchased because of their economic feasibility. Most solar users realize they are not saving money at the present time. However, they know they are saving nonrenewable energy, and they know their added costs for solar energy are not too high. They also know that other energy costs will rise, but at an unknown rate. Many farmers are interested in making use of solar energy, even if it costs more, and they are especially interested in units they can build themselves.

Finally, it should be recognized that most of the solar corn drying research has been based on designs for low-temperature drying such as that developed in Illinois (Shove, 1971). Very little, if any, data are available on the application of solar energy to combination high-temperature, low-temperature drying systems. Very little has been done with the heat pump as an adjunct to a solar system. Little analysis or demonstration has been carried out on solar systems with auxiliary off-peak electrical heat. All of these ideas, and there are probably many more, could make solar applications economically feasible fairly soon in certain areas.

Thus, while much has been done, and we are closer to significant use of solar energy in grain drying, many important questions remain unanswered.

Approved as Journal Paper # 7187, Purdue University Agricultural Experiment Station.

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RICE DRYING WITH IMMEDIATELY APPLIED AND STORED SOLAR HEAT

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INTRODUCTION

The results of solar rice drying research through the harvest seasons of 1975 and 1976 were reported at the Solar Grain Drying Conference, Champaign, Illinois, January 1977, and published in the proceedings (Calderwood, 1977). The results were as follows:

1. Drying time and hours of fan operation were less with solar heat than with unheated air.

2. Electric energy consumption for fan operation was lower with solar heat than with unheated air.

3. A stirring auger was not needed to preserve the milling quality of rice under conditions of the reported tests.

Solar heat was used immediately after collection in 1975 and 1976 rice drying tests; however, during mid-day hours when solar energy is most readily available, the relative humidity of ambient air generally is low enough for drying with unheated air. In their recommendations for using supplemental heat for deep-bed drying, Sorenson and Crane (1960) stated that the temperature of air entering rice may be raised 12 F above outside temperature, but heat should be added only during prolonged periods of high humidity. A method of using solar heat that conforms with Sorenson's and Crane's recommendation is to collect it during the daytime, store it in an appropriate medium, then extract heat at night or other periods when relative humidity of ambient air is at a high level.

The objective of 1977 solar rice drying tests was to determine the suitability of a pebble-bed as a heat storage medium. Items taken into consideration are the construction cost and resistance to air flow of a pebble-bed heat storage unit, the amount of heat collected by solar collectors and a comparison of drying times, electric energy used and milling yields of rice dried with unheated air, with immediately applied solar heated air and with air heated after the time of collection by stored solar heat.

METHODS AND MATERIALS

A facility consisting of four deep-bed rice dryers, a pebble-bed heat storage unit, and three solar collectors, was used for tests of solar rice drying during the 1977 harvest season (Fig. 1). A corrugated steel bin with a 9-ft dia and 11-ft sidewall height, similar to the deep-bed dryers, was used as the pebble-bed heat-storage unit. A perforated metal floor was installed at a level of 18 in. above the base of the bin. The bin was filled with crushed limestone gravel (pebbles) to a height of 9 feet above the floor. The pebbles, having a nominal dia. of 1.5 in., were fairly uniform in size. The density of the pebbles was determined to be 80 lb/ft^3, so the stored limestone pebbles weighed about 22.9 short tons. The storage bin was insulated externally with a 1.5 in. thickness of glass wool.

A solar collector having 320 ft^2 of absorber surface formed a roof along the south side of the row of dryers and was used to supply heat for the pebble-bed. It was inclined toward the south at an angle of 22.5° from the horizontal, a nearly optimum inclination for collecting solar radiation at 30° N latitude during the month of August. Readily available materials were used for constructing this solar collector. These were purchased from a nearby lumber yard at a cost of \$1.36/ft^2 surface area.

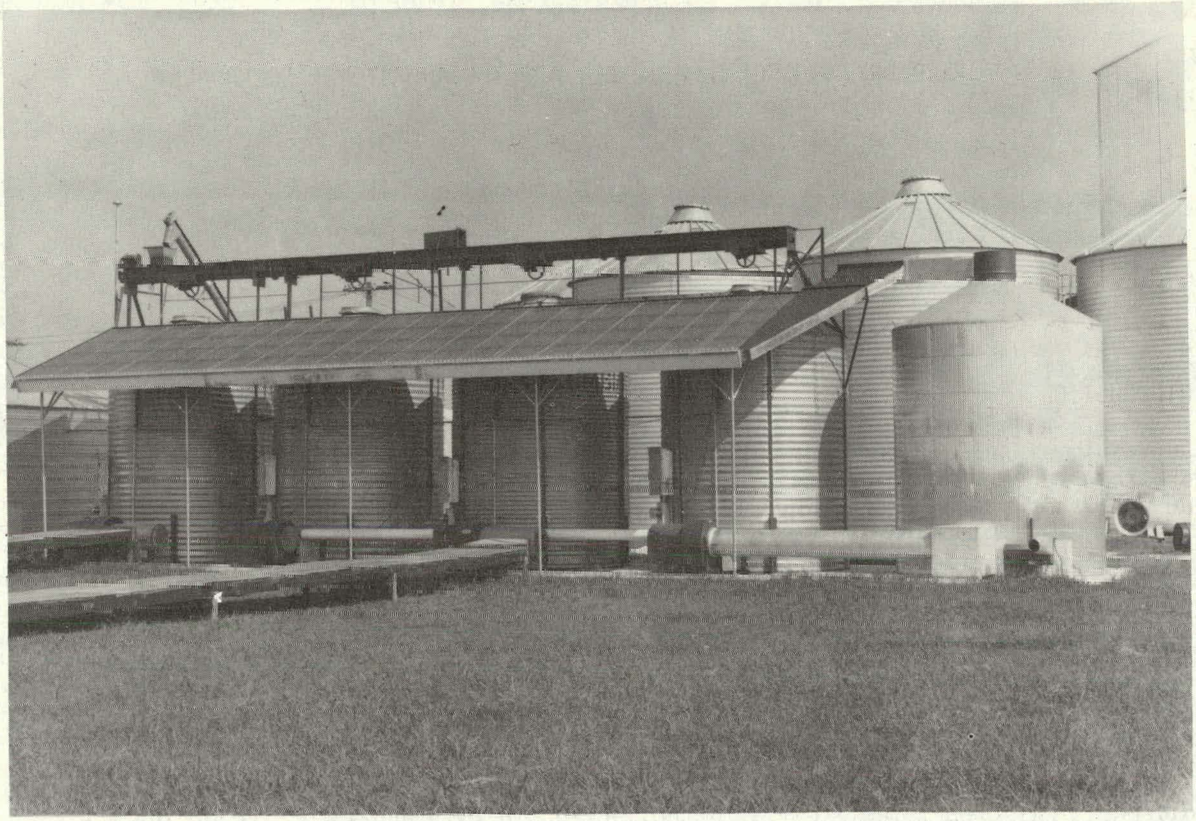

Figure 1. Installation used in solar rice drying tests during 1977 harvest season. From left to right: Dryers 1, 2, 3, and 4 and a pebble-bed heat-storage unit. Also shown are two ground-level solar collectors and a roof-level solar collector.

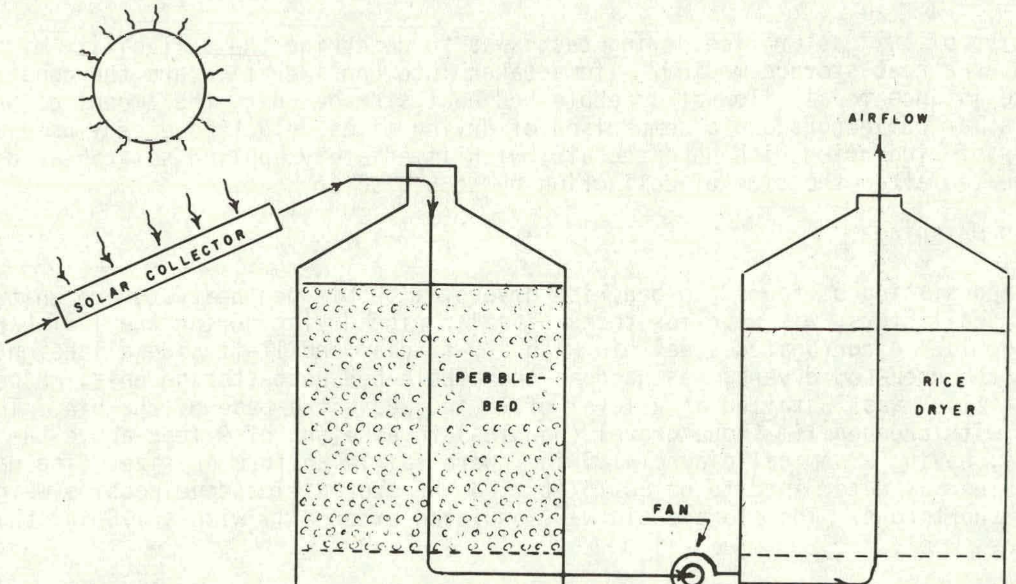

Figure 2. Schematic of air flow in solar collector, pebble-bed and rice dryer. A single fan moved air through the system.

A schematic diagram of the air flow system for the pebble-bed heat storage unit and rice dryer is shown in Fig. 2. The path followed by the air stream was through a solar collector, through the pebble-bed to the intake of a fan that exhausted through a bed of rice and out through the top opening of a rice dryer. Rice in the dryer was stirred with a vertical auger during a daily time interval of 9 hours.

The other three dryers were operated in 1977 just as they had been during the 1976 harvest season. Dryer 1 was supplied with immediately applied solar heat but the rice was not stirred. Dryer 2 was supplied with unheated air, but again, the rice was not stirred; Dryer 3 was supplied with immediately applied solar heat and the rice was stirred during a 9-hr daily interval. The solar collectors for Dryers 1 and 3 were constructed with 192 ft^2 of absorber surface area. Both of these solar collectors were inclined toward the south at an angle of about 5° from the horizontal.

The dryers were filled with an early maturing, long-grain rice variety, Labelle, between July 21 and 23, 1977. Then they were emptied after the rice had dried to a marketable level. The dryers were refilled with second-crop Labelle variety rice from October 14 to 17, 1977 and the tests were repeated. Rice samples were taken at intervals as the dryers were loaded and again as they were emptied after drying was complete. These samples were tested for moisture content with a Motomco[1/] moisture meter. The small samples taken periodically during each loading and unloading operation made up a composite sample for milling yield tests. The composite samples taken during unloading operations were at a suitable moisture content for milling yield tests, but the high moisture samples taken during the loading operations had to be air-dried to about 12% moisture content before they were milled. Both the air-dried and dryer-dried samples were milled in a McGill[1/] no. 3 mill by the standard procedure used by rice graders. Afterwards the amount of total milled rice was determined, then broken kernels were separated from whole kernels so that the amount of whole kernels of milled rice (head rice) could be determined. Milling yields of air-dried and dryer-dried samples from the same lot of rice were compared.

Thermocouple junctions (copper-constantan) were installed at strategic locations where information on temperatures was needed within the dryers, solar collectors and pebble-bed and connected to a 16-point recording potentiometer. Temperature readings for the various locations were taken at hourly intervals. The ambient air temperature and relative humidity were recorded continuously with a hygrothermograph. Another hygrothermograph was used to record the temperature and relative humidity of air leaving the pebble-bed.

An Eppley[1/] black and white pyranometer with an integrating, digital recorder was used to obtain hourly printouts of radiation intensity. Kilowatt hour meters were used to measure the electric energy used for fan and stirring-auger operations and time meters were used to measure the hours of fan operation.

Air flow rates for each drying operation were needed in order to compute the amount of solar heat collected. The rate of air flow for each dryer during two operating periods was determined by two methods. In the first method, the rice depth and static pressure in the plenum chamber were measured soon after loading was completed. Dividing static pressure by rice depth provides the pressure drop per ft of depth. A graph published by Shedd (1953) or Calderwood (1973) gives an equivalent air flow rate in Cfm/ft^2 of floor area. In the second method, the velocity of the air exhausted through the top opening of each dryer and the area of the openings were measured. The air flow rate is the product of velocity x area. Air flow rate data are listed in Table 1. Good agreement between the two methods of measuring air flows was obtained when Shedd's graph was used for dryers with stirring augers and Calderwood's graph used for dryers without stirring augers.

The static pressure drop across the pebble-bed was measured at three air flow rates. These data were used to prepare a graph which shows resistance to air flow of the particular size particles used in the pebble-bed.

1/ *Mention of a tradename or proprietary product does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of products that may also be suitable.*

TABLE 1. Air flow rate in rice dryers as computed by two methods

Dryer No.	Date of observation	Stirring auger used	Depth of fill	Plenum static pressure	Exit air velocity	Air flow rate[1/] by S.P.	Air flow rate[1/] by velocity
			Ft	In.	Ft/Min.	Cfm	Cfm
1	07/28/77	No	7.8	2.45	406	954	942
2	07/28/77	No	7.5	2.80	448	1081	1039
3	07/28/77	Yes	7.2	2.65	530	1177	1198
4	07/28/77	Yes	7.2	1.95	520	954	1206
1	10/17/77	No	8.1	2.50	420	954	974
2	10/17/77	No	7.9	2.90	476	1119	1104
3	10/17/77	Yes	7.4	2.70	534	1170	1202
4	10/17/77	Yes	7.4	2.20	492	1018	1141

1/ Air flow/ft^2 was obtained from pressure drop/ft depth by reference to a graph (Shedd 1953) for dryers with stirring augers, and by reference to another graph (Calderwood 1973) for other dryers. The top opening of Dryers 1, 2 and 4 was 2.32 ft^2 and Dryer 3 had an opening of 2.26 ft^2.

TABLE 2. The effect of solar heat and stirring on drying time, fan operating time, electric energy used and milling yield

Dryer No.	Starting date	Treatment: Solar heat	Treatment: Stirring	Moisture content: Init.	Moisture content: Final	Drying time	Fan operating time	Elec. energy used	Milling Yield[1/]: Air dried	Milling Yield[1/]: Dryer-dried
				%	%	Days	Hours	kWh	%	%
1	07/22/77	Yes	No	19.0	11.5	12	230	211	60.4/68.0	61.1/68.4
2	07/22/77	No	No	19.0	12.1	31	315	297	57.2/66.5	61.1/68.5
3	07/22/77	Yes	Yes	19.2	11.5	11	186	311	58.5/66.2	60.4/68.1
4	07/21/77	Yes	Yes	21.0	12.0	10	245	325	59.7/67.4	62.1/68.9
1	10/17/77	Yes	No	18.9	11.3	24	322	305	60.0/69.3	61.5/70.3
2	10/15/77	No	No	20.0	11.5	30	403	399	61.9/70.0	62.5/70.6
3	10/14/77	Yes	Yes	21.2	12.2	24	359	453	60.8/69.2	60.2/69.8
4	10/14/77	Yes	Yes	21.9	12.2	14	367	426	61.5/69.6	60.1/69.3

1/ $\frac{\text{\% whole kernels of milled rice}}{\text{\% total milled rice}}$

RESULTS AND DISCUSSION

Cost of a Pebble-Bed Heat Storage Unit. The following list shows the cost of materials used for constructing the pebble-bed heat storage unit. Labor costs are not included except for insulating the bin in which the pebbles are stored. The contract for this job included materials and labor.

Solar collector, 320 ft^2 absorber surface	$436
Supporting truss and posts	153
Corrugated steel bin, 9 ft dia	751
Exterior surface insulation	875
Limestone pebbles, 23 short tons (delivered)	236
Air ducts	100
	$2551

Resistance of Pebbles to Air Flow. Static pressure drops of 0.67, 0.22 and 0.06 inches (water gauge) were measured across the pebble-bed with air flow rates of 2320, 1018 and 445 Cfm, respectively, through the pebble-bed. The pressure drops were divided by 9 to obtain the pressure drop/ft and air flow rates were divided by 63.6 to obtain Cfm/ft^2. These data were plotted on full logarithmic graph paper with pressure drop/ft depth as the abscissa and air flow, Cfm/ft^2, the ordinate. A straight line was drawn through the three points (Fig. 3). Also shown in Fig. 3 for contrast are lines for rough rice and soybeans (Shedd, 1953).

Solar Heat Collected. The difference between ambient air temperature and plenum air temperature (temperature rise) for the three dryers that received solar heat are plotted in the graphs in Fig. 3. The amounts shown are averages by hours of the day for entire drying periods. The plenum temperature of Dryer 4 was lower than ambient air temperature during a period of several hours each day. A comparison of hygrothermograph charts of ambient and pebble-bed air temperatures showed that the peak daily temperature of air emerging from the pebble-bed lagged the peak ambient air temperature by 8 hours. The amount of solar heat collected is directly proportional to the temperature rise as follows:

$$\text{kW} = \frac{(\text{Temp. rise, F})\ (\text{Air flow rate, Cfm})}{3000}$$

The average daily energy output for three solar collectors during the July and October 1977 operating periods, respectively, were: Dryer 1, 34 and 20 kWh; Dryer 3, 38 and 21 kWh; and Dryer 4, 68 and 47 kWh.

Drying Times. During the July-August operating period, rice in dryers with solar heat dried to a satisfactory level in elapsed times of 12, 11, and 10 days, respectively, in Dryers 1, 3, and 4; whereas that level of drying required 31 days with unheated air in Dryer 2 (Table 2). Solar heat was less effective for reducing drying time during the October-November operating period. The drying time was 24 days in both Dryers 1 and 3, and 14 days in Dryer 4. Drying with unheated air in Dryer 2 required 30 days.

Electric Energy Used. The use of solar heat reduced fan operating time and electric energy required for fan operation. However, Dryers 3 and 4 with solar heat used more total electric energy than did Dryer 2 with unheated air because of additional energy required for operation of stirring augers even though the augers operated for only 9 hrs each day. Solar Dryer 1 (without a stirring auger) used 29% less electric energy than did Dryer 2 for drying early-harvested rice and 23% less electric energy for drying second-crop rice. Electric energy data are shown in Table 2.

Milling Yields. Percentages of both whole kernels of milled rice (head rice) and total milled rice are shown in Table 2, but only the percentages of head rice were affected by drying treatments. The percentages of head rice from dryer-dried samples were, in most instances, either equal to or greater than the percentage of head rice from air-dried samples of early-harvested rice. A drop of 0.6 and 1.4 in the percentages of head rice can be noted between dryer-dried and air-dried samples of second-crop rice from Dryers 3 and 4, respectively. This amount of quality change was attributed to sampling error and was not considred to be of consequence.

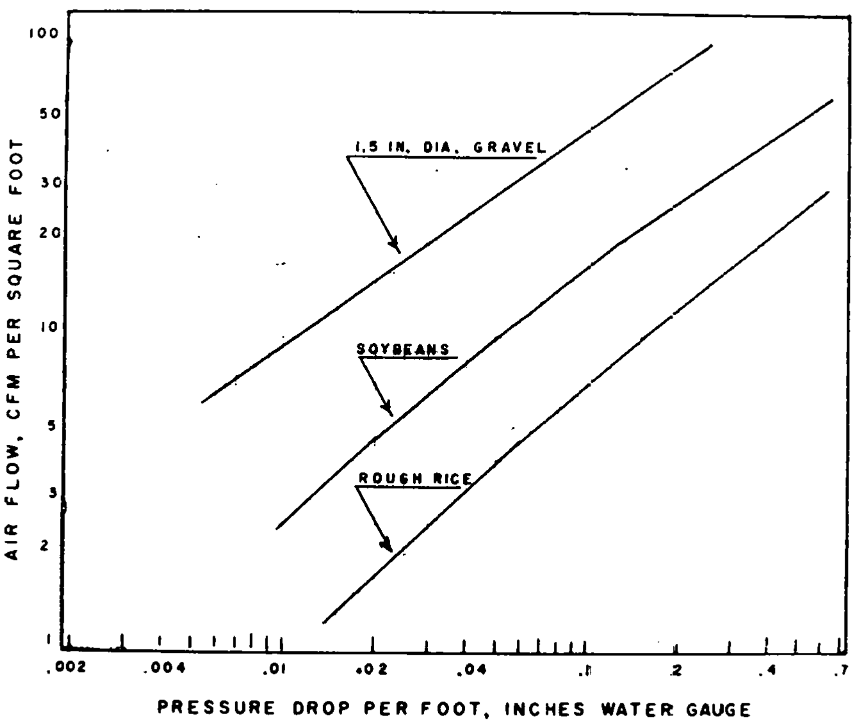

Figure 3. Resistance of 1.5 in. dia gravel (pebbles), soybeans and rough rice to air flow

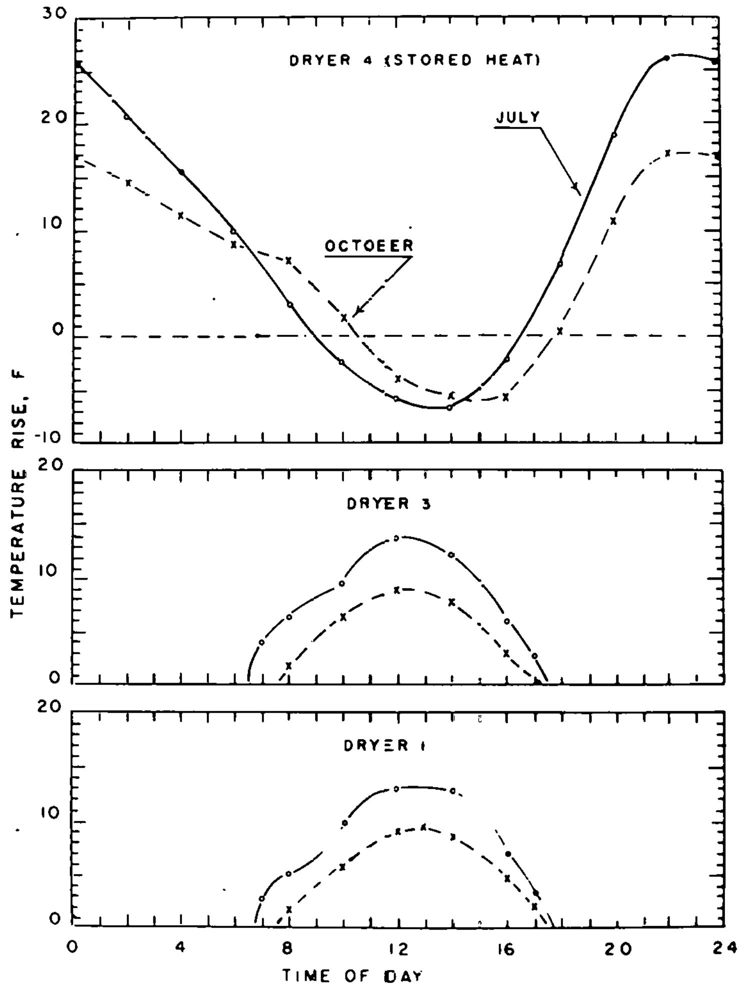

Figure 4. Average temperature rise (or decrease) in plenum chambers of solar rice dryers at different times of the day during drying of early and late-harvested rice

CONCLUSION

A pebble-bed solar heat storage unit did not justify its construction costs under the conditions of these tests. Faster drying with stored solar heat, as compared with immediately used solar heat, is attributed to the large size solar collector used for heating the pebble-bed. The milling yields of rice did not appear to be affected by the drying treatments.

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SOLAR GRAIN DRYING FOR OHIO

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Agricultural crop drying is an area where, because of energy cost escalation and the decline of availability of certain fuels, it is desirable to find low-cost alternate sources of energy. Solar radiation is one such source of energy. However, the effective use of solar energy for crop drying depends on:

i) geographical location;
ii) crop type;
iii) size of operation;
iv) government's economic policy;
and v) attitude of the owner of operation.

i) Geographical location: Solar radiation depends on latitude and meteorological conditions that vary from month to month. A solar drying system depends on available radiation at harvest unless heat is stored prior to the harvest season. Weather data for Wooster, Ohio, shows that an average 19.5 MJ/m^2 (1720 BTU/ft^2) of energy is available daily on a flat horizontal surface from May 1 to October 1, compared to only about 9.4 MJ/m^2 (823 BTU/ft^2) daily during October and November. In addition, location also determines humidities likely to occur during the drying season.

ii) Crop Type: Various grain species are harvested in different seasons and have different physical properties, such as mass diffusivity and thermal conductivity. These factors affect drying rates and determine required air conditions, to achieve safe moisture equilibrium. The experimental studies in 1974-77 at the Ohio Agricultural Research and Development Center, Wooster, (OARDC) indicated that air conditions during October are usually adequate for unheated (natural) air drying of soybeans and corn. Additional heat is required to raise the ambient air temperature by at least 2.2°C (4°F) to dry corn in November, while soybeans can be dried during November with natural (unheated) air. In short, weather and crop type are important criteria for selection, design and sizing of any solar dryer. Table 1 summarizes field studies with corn.

iii) Size of Operation: An important criterion for any drying operation is timeliness. The drying operation must allow the harvesting rate to proceed in an orderly manner. Low-cost, low-temperature dryers may suffice for small farms, while the commercial organizations and large fans may require high temperature dryers.

iv) Government's Economic Policy: The future of solar drying is very much dependent on its being an economically viable alternative. At the current prices, studies at OARDC indicate (Keener, 1977) that natural gas drying is the lowest cost method. Changing government policy on pricing either natural gas or oil could change this drastically. With the improved materials and mass production, the cost of solar collector per unit area could be lowered to make it more competitive. However, this assumes that the inflation rate for collector materials remains low compared to fuel escalation cost. Lease options and inducements by the government in the form of low interest loans and investment tax credit would also affect the adaptability of a solar dryer.

v) Attitude of the Owner: The use of solar dryers on a commercial scale is somewhat recent and the economic viability is not proven. Their success depends a great deal on the willingness of owners to take risks. It is important for the manufacturers of the solar drying systems to give essential training to the buyer, because his/her results and experiences will probably influence the adoptability of solar dryers in a local community.

In short, there are many factors which may influence the justification of a solar dryer at present, but with rising fuel costs and scarcity of fossil fuels, a farmer may have no choice in the future.

Solar Drying Studies in Ohio: One of the foremost problems, in utilizing solar energy for heating, is the large variation of solar radiation available from day to day. This variation makes solar energy a non-deterministic source and any drying systems based on solar energy must compensate for this fact. One way to compensate is to design the drying system so that grain drying can occur over a long period of time, say 6-30 days, without the grain going out of condition. With this process, instantaneous solar collection can be used as a heat source and the system designed on the basis of time averaged values, (Sabbah, 1977). This method of drying, however, may not work when the crop is harvested at high moistures (and/or high ambient temperatures). Another way to minimize the effect of solar variability is to provide for solar energy heat storage, so that during the drying season, energy previously collected will be available.

Computer simulation studies (Figures 1, 2) have shown that raising the ambient air temperature 2.2 - 4.4°C (4-8°F) would satisfactorily facilitate the drying of Ohio's corn crop during October and November. This requirement may be met with a low temperature collector and could be obtained by instantaneous use of solar energy. Such experiments were performed from 1974-77 using an instantaneous SOLORON* solar collector, for drying corn at Wooster during October and November. Work on two ways of storing solar heat in water, namely, by a high temperature solar collector, SUNPAK™**, and by a solar pond method, are now in progress.

Instantaneous Collection: SOLORON is an air-supported quasi-suspended plate collector and the one used in Ohio's studies had an area of 90.3 sq. meters. It has two chambers through which air is moved (Fig. 3) and most of the radiation is absorbed by the suspended translucent vinyl layer. Chambers were kept inflated by the air blown through the collector. Heat energy collected from the SOLORN is shown in Fig. 4 along with the local fluctuations of the radiation. Its efficiency depended on the weather and varied each day. Based on observations during the autumns of 1974-77, this collector had about 32-40% collection efficiency when maintained on a horizontal plane and supplied with an air flow of 1.41 cc/(hr.-sq. m.) (2 cfm/ft^2).

Experiments were also performed with the bottom of the collector insulated from the ground as well as uninsulated. Results showed that, during October and November, a SOLARON with uninsulated bottom was just as efficient as one with an insulated bottom.

Conclusions based on the 1974-77 grain drying studies were:

1. Operation of low temperature grain drying (possibly solar heated) requires grain moistures at harvesttime to be below 25% to enhance feasibility.

2. Field studies show corn kernel moistures below 25% early in October in Ohio are feasible without sacrificing through the use of proper hybrid selection, nutrient application, planting date and pest control.

3. In October, natural air drying is practical as a means of drying grain successfully.

4. In November, some heating of the air is desirable to improve drying efficiency (possibly solar supplemented).

5. On a total systems basis, natural air drying between 25% and 20% moisture and low-temperature heated air drying below 20% is the most energy efficient way to dry.

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* Manufactured by Solar Energy Products Co., Avon Lake, Ohio.
** Manufactured by Owens-Illinois, Toledo, Ohio.

6. For bin drying, depths should be kept below 3.7m (12 feet) under Ohio's weather conditions. Optimum drying depths are nearer to 0.9 to 1.2m (3-4 feet) with fan horsepower below 8 kw per 100 sq. meters (1 hp per 100 sq. ft.) of bin floor area.

7. From a management standpoint, two-stage bin drying is most desirable.

Long-Term Storage: Long-term, large-quantity energy storage for grain drying has an inherent desirability over short-term, low-quantity storage since large quantities of energy in storage have the potential of supplying uninterrupted energy to eliminate the risk factor in drying grain and establish more confidence in the minds of farmers. When properly designed, long-term storage may become cost competitive even though it requires more capital initially.

Experimental studies of long-term storage are very expensive and time consuming. Thus, computer simulation, utilizing parameters based on specification of SUNPAK™ high temperature solar collector, is being used to explore the feasibility of long-term heat storage. In addition, field data on a solar pond (Short, 1977) is available for verification of part of the simulation work.

The SUNPAK™ collector (Fig. 5) consists of modules which can be joined in series. The number of modules required depends on the demand for heat energy. Each module consists of 24 glass tubes, 12 on each side of the central water feeding trough. It is an evacuated - tube type collector and has negligible convective heat losses to the atmosphere. One module occupies about 3.0 sq. m. (32.0 sq. ft.) area and has collection area of about 2.6 sq. m. (28 sq. ft.). Detailed discussion is provided in Owens-Illinois, 1975 literature.

Wooster weather data from May to September for the years 1970-77 was used in our simulation to evaluate how solar energy could be collected and stored for use in corn drying in October through November (Table 2). Studies indicated that 1975 had the lowest radiation level (May through September) of the years studied. Thus, 1975 weather data is being used for solar heat storage in current simulation studies. A plot of 1975 radiation compared to the 13-year average is shown in Fig. 6.

Design of the hot water storage tank is very important for successful heat storage. Tank capacity, insulation type and its thickness on tank sides, location of tank (above-ground or in-ground), the thermal characteristics of storage tank walls and location of inlets and outlets are some of the parameters to be studied in detail. A study has begun to determine some of these parameters to meet a demand of about 174 G Joules (165 million BTU's), during October and November corn drying season in Ohio. This quantity is necessary for drying 254 K tonnes (10,000 bushels) from 25% (w.b.) to 15% (w.b.) at 60% heat exchanger efficiency. All of these parameters are interlinked with each other and will require further reevaluation as more and more factors are taken into consideration.

Tank Size: In preliminary studies, allowing no heat loss from the tank, it was found that a 545,000 liter (145,000 gallon) capacity water tank would be minimum for storing 174 G Joules (165 million BTU's) of recoverable heat energy. A water temperature of about 95°C (Table 3) could be expected when using 80 modules of SUNPAK™* collector, whereas water could be expected to boil in a tank of lesser capacity. An economical analysis could have been made to find the optimum number of tubes and tank size but was not undertaken at this point because the tank capacity was simulated without any heat considerations. In practice this would not be the case.

To analyze the effect of surrounding soil temperatures on the heat loss from an uninsulated in-ground tank, a 726,000 liter (193,000 gallon) tank excavated into the ground, Figure 7, was considered. The following assumptions were made for analysis.

i) Soil temperature below 3.1m (10 ft.) is 12.8°C (55°F) and is constant.

ii) Tank water temperature is affected only by 1.8m (6 ft.) of the surrounding soil temperature, i.e. tank and 1.8m (6 ft.) surrounding soil are embedded in an infinite region.

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* Use of the SUNPAK™ name is only for the purpose of indicating a set of performance specifications used in simulation. Other brands of evacuated collectors are also being made.

iii) Tank is made of about 5 cm (2-inch) thick stone concrete and has over-all unit conductance of 0.42 kcal/(sq. m-hr.-°C).

iv) Temperature gradients throughout the soil are linear.

v) From the surface to a depth of 0.9m (3 ft.) a dry soil thermal conductivity of 0.36 kcal/(m-hr.-°C) was used. Below 0.9m (3 ft.), a wet soil thermal conductivity of conductivity of 2.23 kcal/(m-hr.-°C) was used.

vi) A free water surface to the atmosphere exists.

vii) 80 modules of SUNPAK™ collector were used.

Simulated water temperature on September 29 under the above conditions reached only 28.8°C (Figure 8) compared to 76.9°C for the perfectly insulated tank. Only about 24.2% of the heat energy was stored in the ground storage tank compared to a perfectly insulated tank. It was anticpated before analysis that surrounding soil, in case of an in-ground tank, may serve as temporary heat storage, too, and some heat could be recovered from it. However, analysis at this stage indicates that surrounding soil is behaving like a heat sink.

Extensive simulation studies to optimize cost of storing heat (long-term heat storage) in aboveground and in-ground (excavated) tanks are now planned. Cost of the long-term heat storage system would include cost of erection/excavation, materials (insulation, liners, collector), maintenance and operation. Energy storage analysis will consider the actual tank construction and the effect of insulation thickness, volume of water and number of collector modules to find the most cost-efficient combination which will store a specific amount of heat in 1975 (lowest summer radiation for 1970-77) at Wooster, Ohio. It is also planned to examine the effect of the shape of the tank on the cost and energy storage. This simulation study is expected to yield the optimum number of SUNPAK™ solar collectors, water volume, insulation thickness and shape (width and height/depth) of aboveground and inground (excavated) storage structures to store a specific amount of heat.

In the present analysis, the high cost collector SUNPAK™ is being used because it is commercially available and represents a collector capable of producing water temperatures over 82.2°C (180°F) without losing performance. However, there will be a provision in the computer program to use any solar collector and it is planned to run the analyses for low cost types of collectors. Examples are the inflated plastic collector by Mears (1978) in New Jersey, a trickle collector located above the water storage structure, used by Dickey et al. (1976) in Virginia, and the solar pond of Short, et. al. (1977) at Wooster, Ohio. Currently efforts are underway to develop the computer programs for these collector performances.

The completion of this analysis should provide, in detail, feasibility of long-term heat storage for fall grain drying for Ohio (Wooster) type weather conditions. It should also provide a very general, easy-to-use computer program which could simulate long-term heat storage in water for any type of collector system whose performance is known and for any part of the country by input of local parameters, such as geographical location and weather data.

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TABLE 1. Field Studies 1974-77 on Electrical Energy Consumption During In-Bin Corn Drying (Batch)

Starting Date	Drying System	Fan Size Hp.100 ft^2	Grain Moisture % w.b.	Grain Depth Ft.	Air Flow cfm/bu	Drying Time Hr.	Energy Input Kwh/bu	Energy Input Kwh/bu/pt
11/16/74	Solar, Int*	2.0	24.7 - 17.1	2.2	13.8	192	0.55	0.072
11/16/74	Natural	1.0	24.5 - 17.5	1.6	14.4	192	1.22	0.173
11/16/74	Solar	2.0	24.5 - 15.7	2.2	13.8	192	2.04	0.231
10/27/75	Solar	2.0	20.7 → 14.5	2.7	11.8	121	1.1	0.182
10/27/75	Natural	2.0	22.7 → 15.9	2.7	12.8	193	1.6	0.233
10/27/75	Solar, Int*	2.0	10.9 → 15.4	2.7	12.8	170	0.9	0.158
11/13/75	Solar	2.0	20.9 → 15.2	3.0	11.0	152	0.8	0.147
11/13/75	Natural	2.0	20.6 → 15.8	3.0	11.4	224	0.9	0.191
11/13/75	Solar	2.0	20.8 → 15.2	3.0	11.3	200	0.7	0.130
10/14/76	Solar	2.0	27.9 → 15.4	3.0	14.0	119	1.2	0.096
10/13/76	Natural	2.0	28.0 → 16.5	2.8	14.1	160	1.4	0.125
10/14/76	Solar	2.0	26.3 - 15.1	2.8	14.1	119	1.2	0.107
10/28/76	Solar	2.0	27.3 - 15.4	3.6	12.2	236	2.0	0.164
10/28/76	Natural	2.0	25.6 - 15.9	1.8	21.9	147	2.0	0.208
10/28/76	Solar	2.0	27.1 - 15.4	3.4	12.0	284	2.5	0.210
10/13/77	Natural	2.0	22.4 - 14.2	5.1	~7.0	368	1.8	0.219
10/13/77	Natural	2.0	22.1 - 15.8	2.4	15.5	144	1.4	0.224
10/13/77	Solar	2.0	22.9 - 14.4	2.8	13.5	144	1.5	0.176
10/20/77	Natural	2.0	19.5 - 14.4	2.8	12.9	194	1.6	0.317
10/20/77	Solar	2.0	22.8 - 13.8	3.2	11.8	194	1.8	0.198

* Day operation only

Keener, Misra
OARDC, 1978

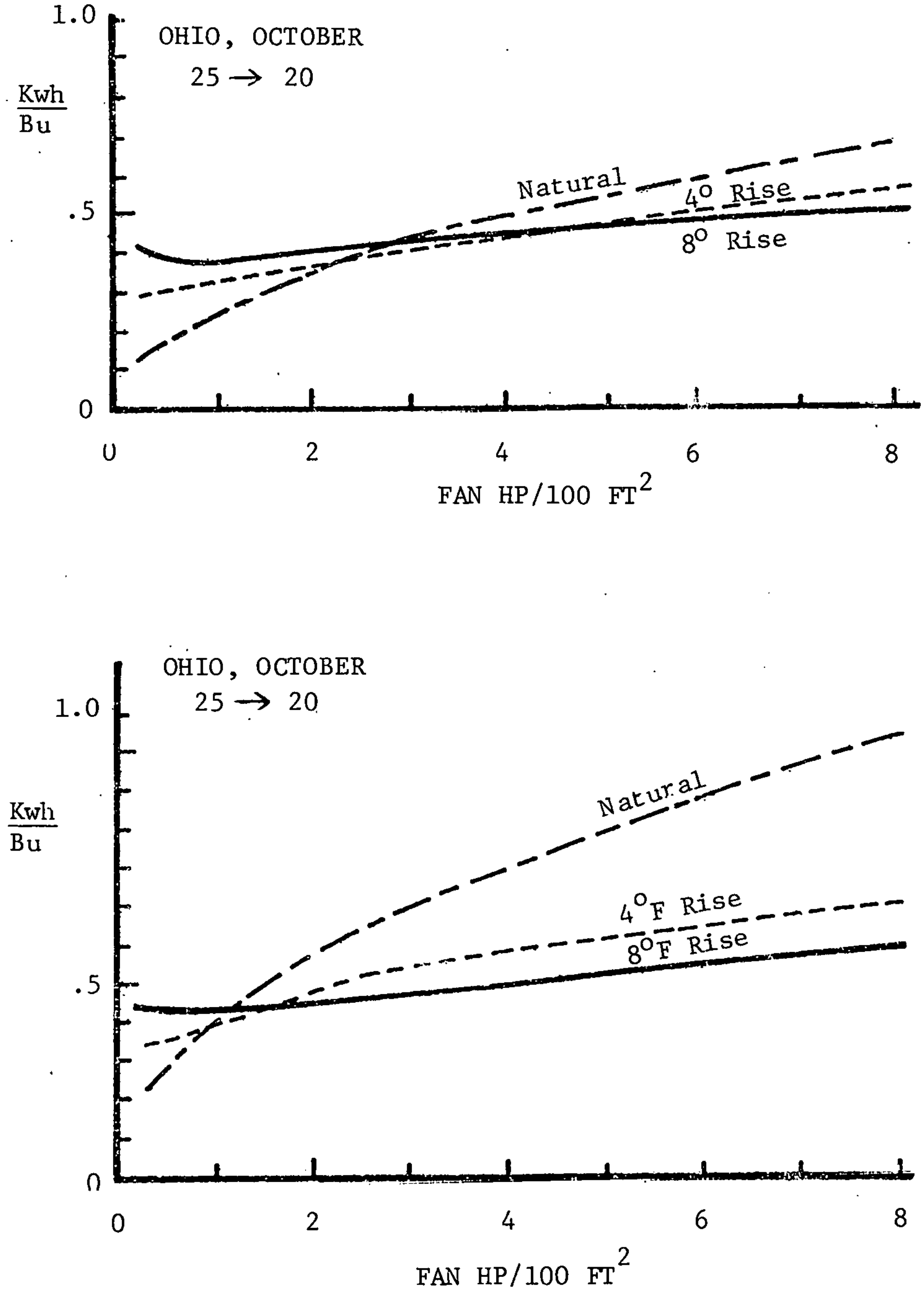
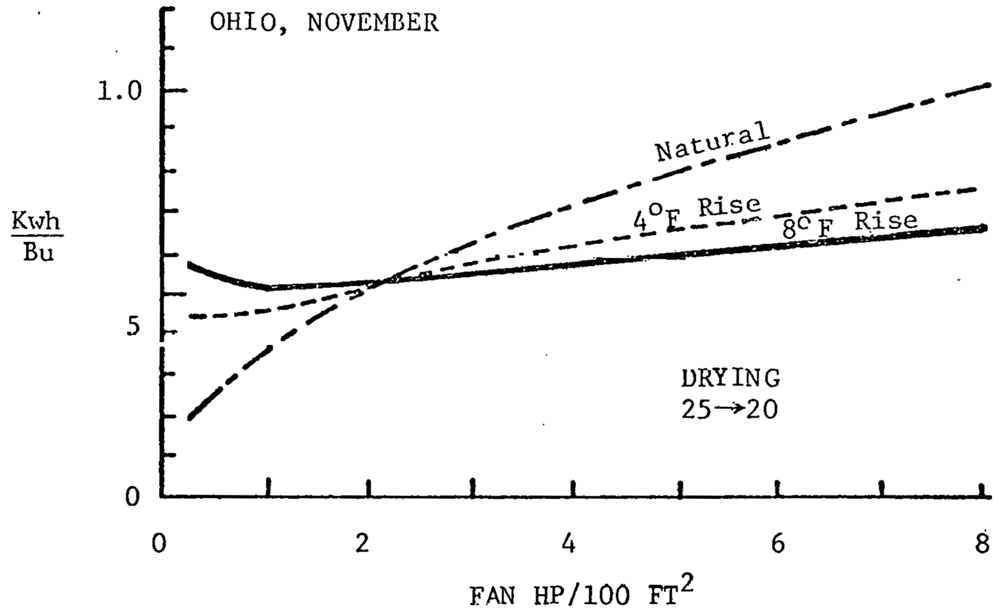


Figure 1. Effect of fan HP on energy efficiency of drying during October in Ohio. Heat source supplied 4 units of heat for each unit of electrical energy used.



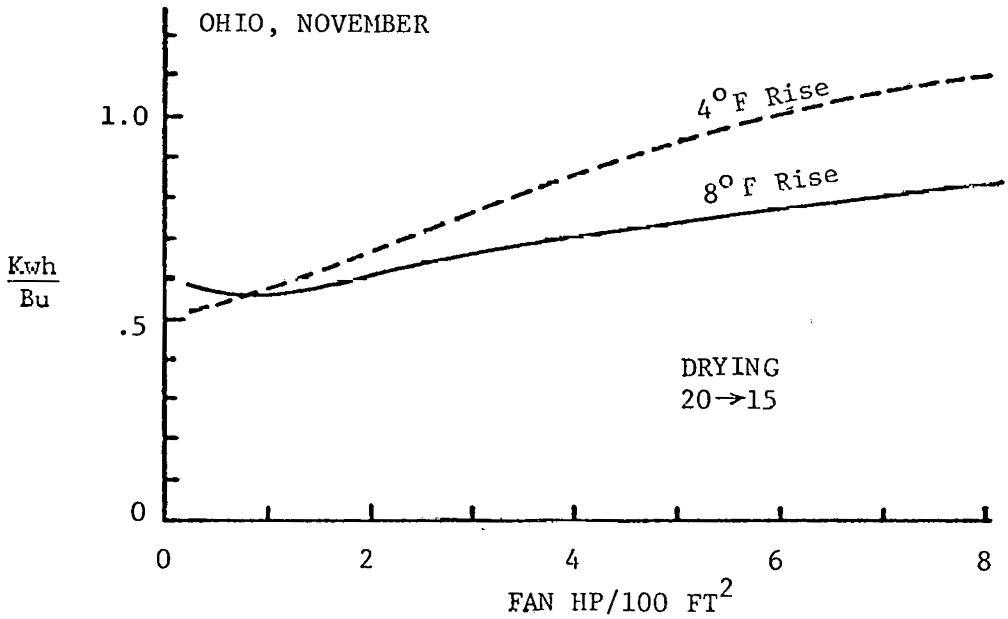


Figure 2. Effect of fan HP on energy efficiency of drying during November in Ohio. Heat source supplied 4 units of heat for each unit of electrical energy used.

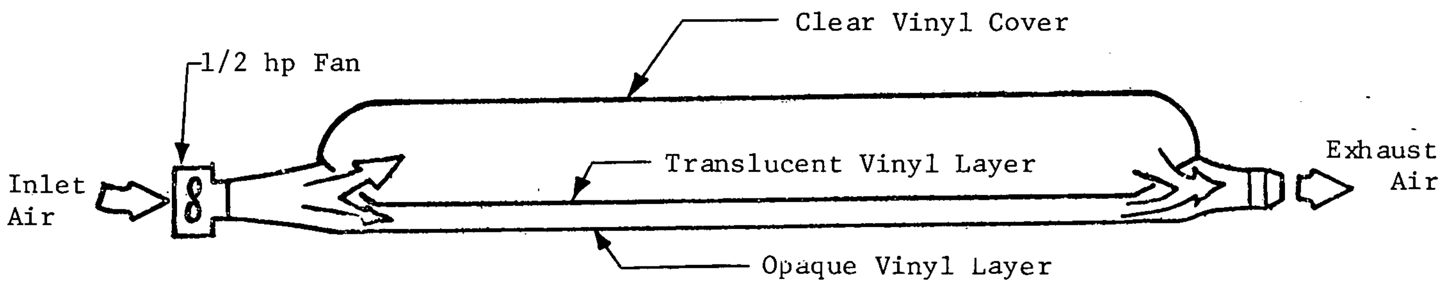


Figure 3. Soloron air supported plastic solar collector.

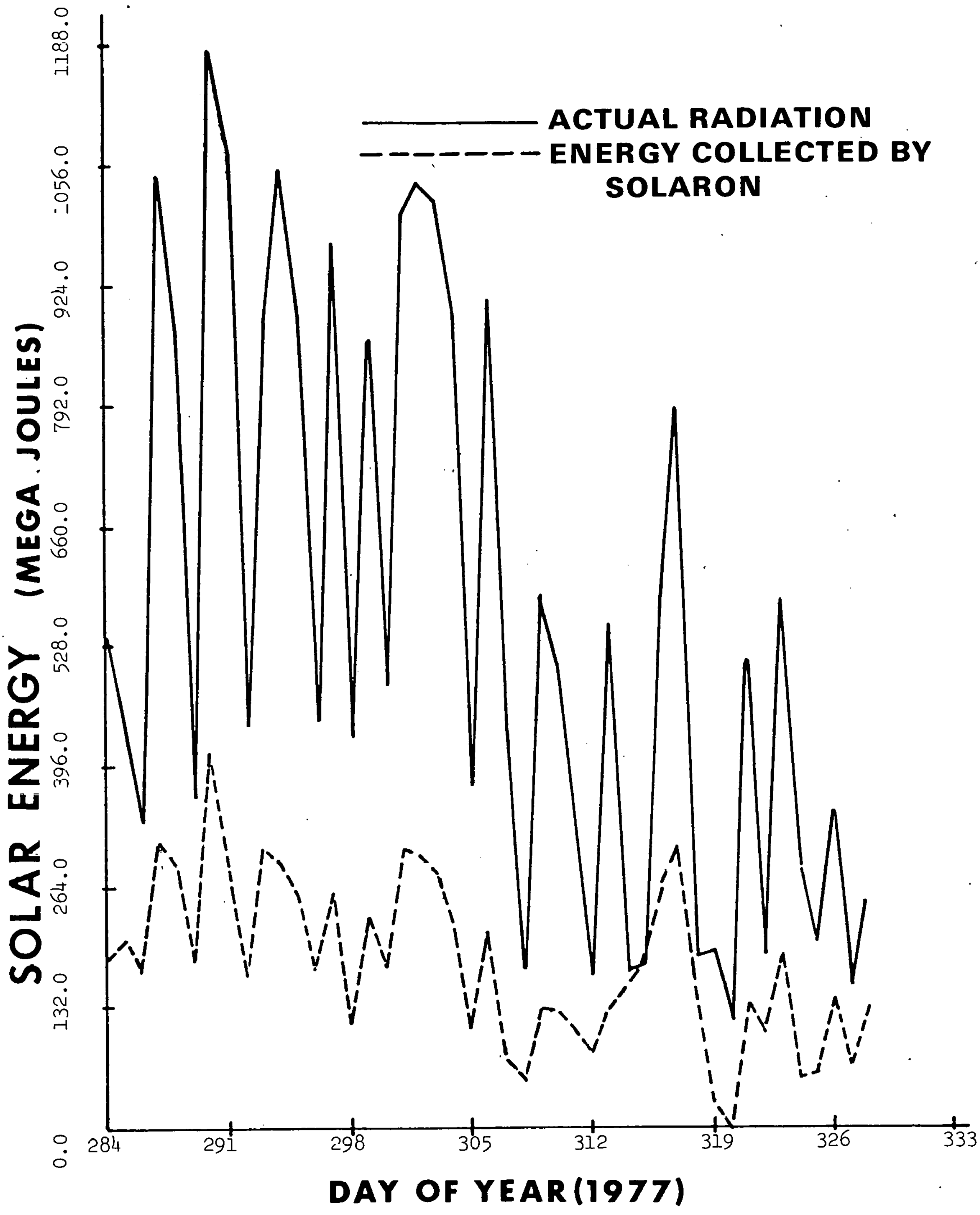


Figure 4. Daily Performance of SOLARON solar collector for fall of 1977. Collector size 90.3 m^2.

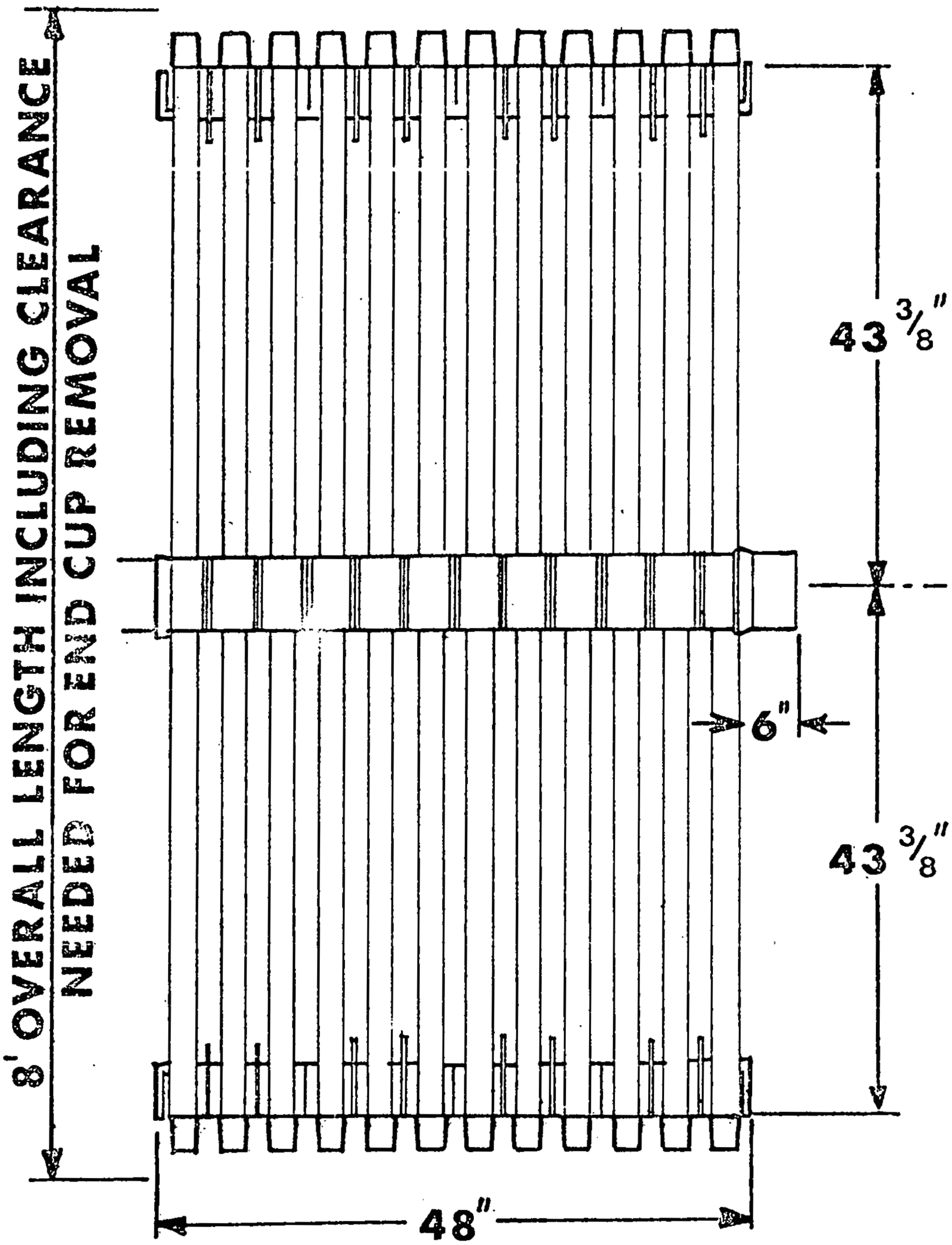


Figure 5. Plan view of a module of SUNPAK™ solar collector.

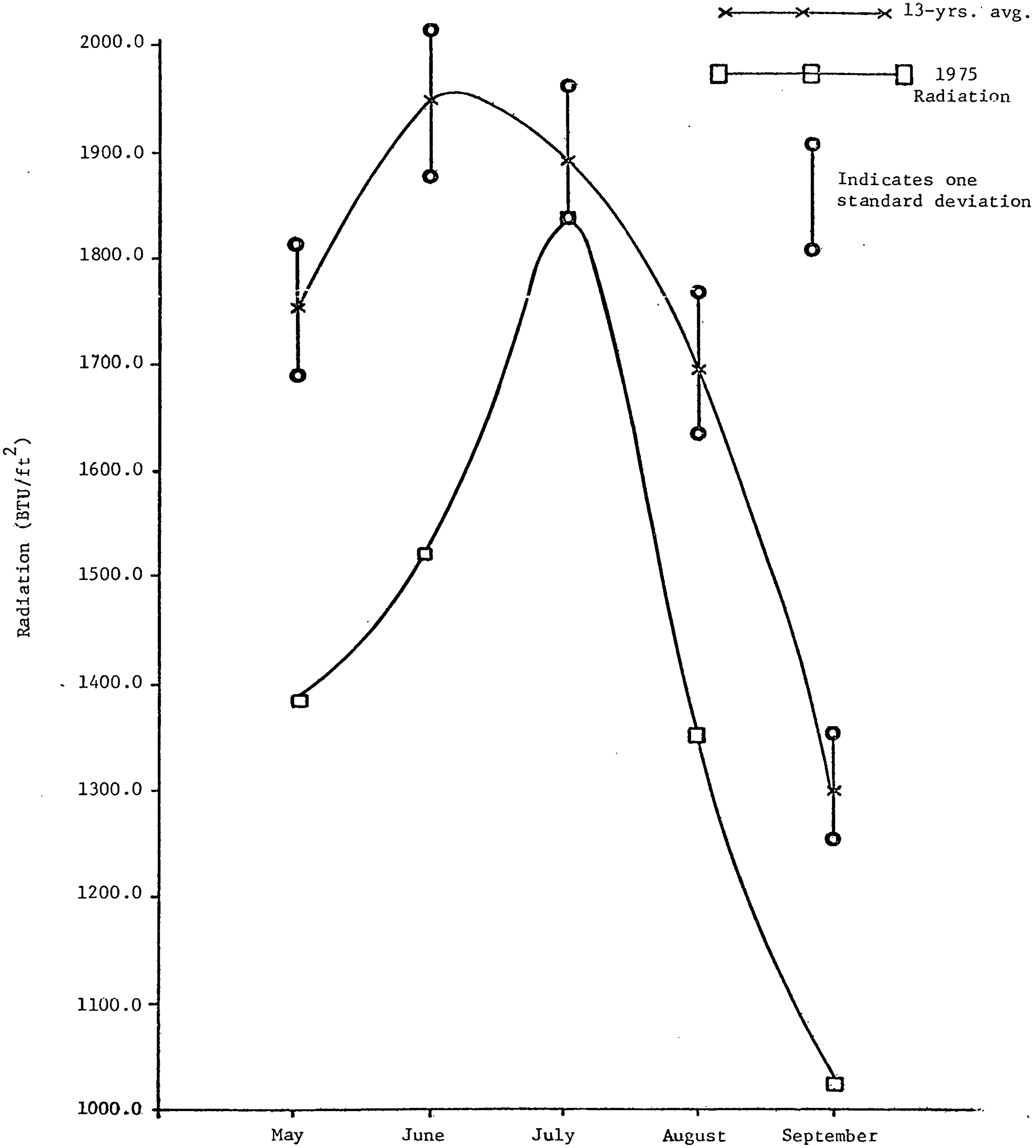


Figure 6. Radiation levels during summer 1975 compared with 13-year average for Wooster, Ohio.

Table 2. Comparison of Temperature* of 726,000 liters water storage tank, with 1920 tube Sunpak™ solar collector, for years 1970-77.

Calendar Day	Water Storage Tank Temperature** for Year (°C)							
	1970	1971	1972	1973	1974	1975	1976	1977
May 1	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
May 15	20.8	18.7	19.1	18.8	19.3	20.4	20.3	19.6
May 31	31.1	28.1	27.7	24.9	27.5	25.7	27.6	30.8
June 15	39.2	35.6	35.7	33.6	36.3	30.9	35.8	37.0
June 30	47.6	44.3	40.5	40.7	42.1	38.0	42.8	45.2
July 15	55.1	52.6	46.4	48.8	50.7	45.3	55.8	53.8
July 31	63.0	60.7	54.1	55.6	58.7	53.8	56.8	62.4
Aug. 15	71.4	69.0	61.1	62.6	65.9	60.3	62.6	68.5
Aug. 31	81.2	77.6	68.9	70.8	72.6	66.8	71.1	75.9
Sept. 15	89.7	83.7	75.9	78.8	78.4	73.4	79.4	81.8
Sept. 29	96.3	88.4	81.2	85.5	84.8	76.9	84.6	85.9

* With no heat loss considered from water storage tank and assuming water from well to be at 12.8°C.

** Water temperature at Noon.

Table 3. Comparison of temperatures* of several tank capacities for 1975 weather data.

Calendar Day	Water Storage Tank Temperature** for Tank Capacity (°C)			
	363,000 liters	545,000 liters	726,000 liters	1,089,000 liters
May 1	12.8	12.8	12.8	12.8
May 15	27.9	22.9	20.4	17.8
May 31	38.2	30.0	25.7	21.3
June 15	48.1	36.9	30.9	24.9
June 30	61.3	46.1	38.0	29.6
July 15	74.8	55.6	45.3	34.5
July 31	89.9	66.6	53.8	40.3
Aug. 15	100.7***	74.8	60.3	44.8
Aug. 31	111.7***	83.00	66.8	49.3
Sept. 15	121.1***	91.1	73.4	54.0
Sept. 29	124.9***	95.05	76.9	56.6

* With no heat loss considered from water storage tank and assuming water from well to be at 12.8°C.

** Water temperature at Noon.

*** Simulated results. (Above boiling temperature not possible without pressurizing tank.)

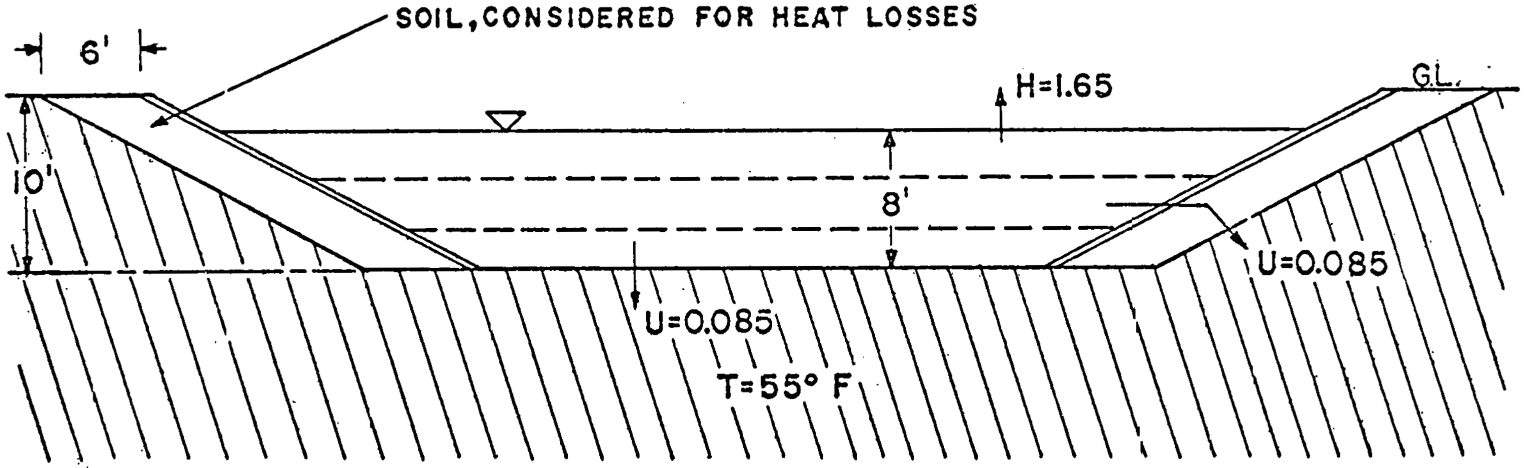


Figure 7. Schematic of In-ground Solar Heat Storage Tank.

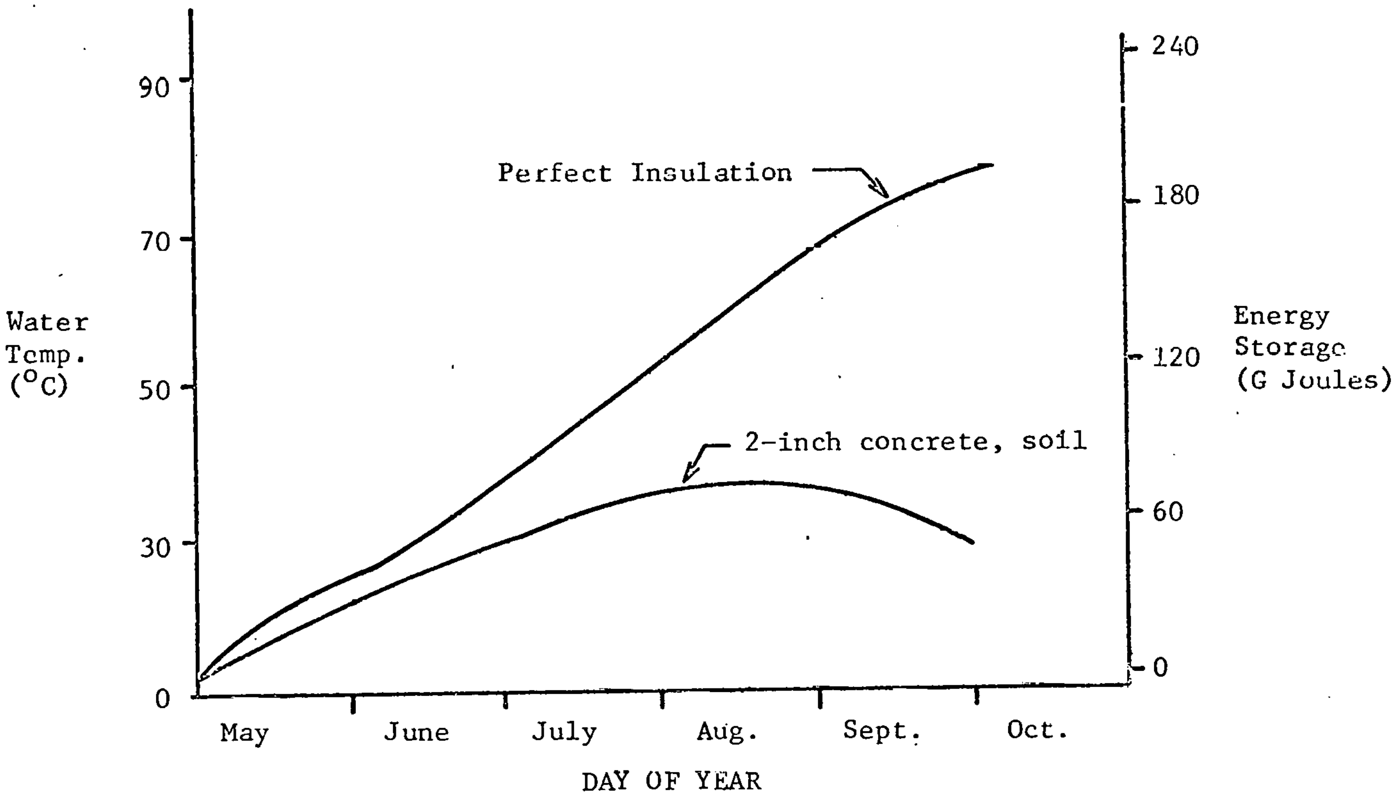


Figure 8. Comparison of insulation on energy storage in a buried water tank.

SOLAR ENERGY COLLECTION AND STORAGE FOR GRAIN DRYING AT HIGH TEMPERATURES

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Grain harvested at 20 to 30% moisture content in the Southeast during warm weather must be dried within a few days to prevent spoilage. This usually involves some type of heated air drying with drying air temperatures in the range of 125 to 200°F. In this study high-temperature heat from a focusing solar collector is considered as an alternative to fossil fuels in heating the drying air.

A sun-tracking focusing solar collector for heating air to temperatures between 250 and 350 F has been constructed and installed. Limited operation of the collector indicates efficiencies between 30 and 50% at outlet temperatures between 250 and 320 F. The use of crushed rock as a heat storage medium has been studied. Data from seven rock bed units show that the pressure drop due to air flow and the rate of heat transfer between the heated air and the stone can be predicted using data from the literature for flow through porous media. For accurate predictions the limestone should be of uniform size. A small grain bin has been constructed to utilize the heat energy stored in the rock bed units. Three of the 1150-pound rock bed units will be utilized at once to provide heat for drying a 9-bushel batch of grain.

Operation of the collector, rock storage and the grain drying processes have been individually simulated on the computer. An economic feasibility study has also been carried out using a range of solar system costs, fuel costs, and interest rates. At today's fuel prices, high-temperature solar grain drying cannot economically compete with LP Gas; however, technological improvements, higher prices for fossil fuels and multiple use of the solar system as a farmstead heat energy system might well make such a system feasible in the future.

THE SOLAR COLLECTOR:

The design of the solar collector is illustrated in Figures 1 and 2. Figure 1 illustrates a cylindrical parabolic reflector which has a reflective surface of aluminized polyester (FEK-163 film, made by the 3-M Company) to reflect approximately 85% of the direct-beam solar energy. The film and surface must be such that a regular mirror-like reflection is obtained so that the solar rays are focused near the center line of the transparent pipe. The air flow through the two glass pipes is illustrated in Figure 2, with the entering air surrounding the small glass pipe containing 24 aluminum fins which are geometrically formed as shown in the end of the small glass pipe. These fins reflect the solar rays twice before being focused near the center of the small glass pipe. The fins are made reflective at approximately 85% reflection up to the angle of the fins. Below the angle the fins are made absorptive to absorb the solar rays. A selective surface consisting of potassium permanganate is used so that rays which are not absorbed will again be reflected in a regular mirror-like angle, thus achieving multiple reflections until most of the energy entering the finned section is absorbed. Re-radiation from the hot fins is transmitted back to the small glass pipe where the glass absorbs the long wavelength radiation. Heat from the glass is partially absorbed by the entering air stream which circulates around the smaller glass pipe. The air then flows over the fins which provide a large heat transfer surface area for transferring the heat from the fins to the air.

The investigation reported in this paper No. 78-2-70 is in connection with a project of the Kentucky Agricultural Experiment Station and is published with approval of the Director.

This solar collecting system with a sun-tracking device has been operated since September, 1977. The outlet temperature of the collector has generally been between 250 and 320 F, with efficiencies in cold weather of approximately 30 to 40%. As the weather has warmed up in the spring, the range in efficiencies has increased to 40 to 50% of the direct-beam solar radiation. The quantity of solar energy incident annually on a tracking solar collector is approximately equal to that available on a flat plate collector if both collectors are oriented due south and sloped at an angle equal to the latitude. This approximate value was developed through a computer program for this project in order to have an appreciation of the approximate energy available on an annual basis. It is presumed that a focusing collector would collect heat all year and be applied to multiple uses in order to improve its economic viability.

HEAT STORAGE IN CRUSHED LIMESTONE:

This project has included a considerable effort devoted toward the study of heat storage in crushed limestone. This is because a very large heat storage unit would be needed with a field of focusing collectors. The alternative storage medium is generally accepted as washed river gravel, which in Kentucky costs approximately $10 per ton compared with $3.00 per ton for crushed limestone. In considering the design of a rock bed several characteristics are important, i.e., heat capacity, heat transfer rate between the air and the stone, the pressure required to force air through the bed, the uniformity of flow in the bed, heat conduction and convection in the bed, and dust, lint and moisture in the bed.

The literature available on flow in porous media and our experience show that convection of heat in a rock bed is minimized or non-existent if the charge of heat is made from the top of the bed toward the bottom. Conduction of heat in the bed is also very small but may be of significance where long-term heat storage (several months) is attempted. The problems of dust and lint could be serious if an established rock bed is to serve for 15 or 20 years or more as a heat storage. To minimize this problem, the air should be filtered to make certain that lint and dust do not fill the void spaces where the air enters the rock bed. Any rock bed should be protected from moisture with a good gravity drain and with a moisture barrier if it is constructed where vapor or liquid water could enter the bed. In addition, if the rock bed is utilized on a cooling cycle where warm humid air comes in contact with cool rock, moisture may condense on the rock. Such conditions should not exist for a long period of time since mold growth and other biological activity might become a problem. Dust on the crushed limestone probably cannot be completely eliminated since washing the stone leaves dust particles which are loosely attached to the limestone. Our experience shows that we have received very little dust from our rock bed with a flow velocity of 10 feet per minute entering the bed (that is a velocity of 10 ft./min. in the space immediately before the air enters the bed).

Crushed rock properties are shown in Table 1. To study the other characteristics listed above, all properties were determined for the specific types of stone used in the seven-unit four-ton rock bed illustrated in Figure 3. The characteristic dimension for computing heat transfer and pressure drop in the bed is the equivalent spherical diameter.

The air distribution in the bed needs to be uniform. One way to achieve reasonably uniform distribution is to use stone which has been graded within a narrow size and to use either a loose fill or a uniform compaction process as the rock bed is filled.

A second procedure in achieving uniform air distribution is to use a low entrance and exit velocity at the rock face and to design for a pressure drop of approximately 0.15 inch of water through the bed. The low air velocity entering and leaving the stone will prevent the velocity from unduly influencing the air distribution, and the back pressure can then control the air distribution if a uniform bulk density of stone has been achieved.

The pressure drop in a bed of crushed rock of uniform size and bulk density can be approximated by using the following equation:

$$\Delta P/L = 8.298 \times 10^{-7} \frac{V^2\rho}{d} \left[42 + 21. \times 10^5 \frac{\mu}{V\rho d}\right]^*$$

where: $\Delta P/L$ is the pressure drop in inches of water gage per foot of bed length

V is the velocity of air at the rock face; $V = \frac{\text{CFM}}{\text{Rock-face Area}}$

d is the particle diameter in feet

ρ is the specific weight of air in pounds per cubic foot and

μ is the viscosity in pounds per foot second.

The data we have taken on uniformily sized crushed limestone correlate quite well with this equation. Future work may show that a better equation can be developed, but at this time we believe this equation will give a reasonable approximation of the pressure drop in crushed stone of uniform size and bulk density.

The heat transfer from the air to the stone has also been studied both theoretically and experimentally. The results of this work show that our computer program based on the differential equations of heat flow between the stone and air can provide a good approximation of the rates of heat flow. It also indicates that if the stone is heated from the top a highly stratified storage of the heat is obtained. The computer program shows that the smaller the stone, the more rapidly the heat is absorbed, the better the heat stratification and on withdrawl the higher the recovery temperature. Therefore, from the practical standpoint the most highly stratified bed which will return the most heat at the highest temperature is the bed which has the smallest stone. However, the smaller the stone the greater the pressure drop. Thus, a rock bed should, from a practical viewpoint, be designed using the smallest stone which will still result in a reasonable resistance to air flow. Based on the equation presented above, the pressure drop may be determined and the bed face area and size adjusted to achieve desirable air distribution as well as a highly stratified rock bed.

GRAIN DRYING:

The model solar grain drying bin is illustrated in Figure 4 and its connections to three units of the rock bed are illustrated in Figure 5. Thermocouples are located 6 inches on center to indicate the drying front as drying progresses up the column. Corn and soybeans will be dried in 4 to 10-bushel quantities. The rate and efficiency of drying and the quality of grain dried will be determined.

ECONOMICS:

The degree to which money may be invested in solar grain drying equipment is primarily a function of equipment cost, expected life of the equipment, payback period, interest rate and the price of fossil fuel. If the life of the equipment is 20 years and 10 points of moisture are to be removed from the grain, approximately $1,000 could be invested in solar drying equipment for each 1000 bushels of grain to be dried assuming L.P. Gas was selling for $0.40/gallon and the interest rate on money was 5%. This also assumes that the operating and maintenance costs will be the same for solar equipment as it is for conventional equipment and does not consider possible tax advantages. The amount of fuel to be used in drying each bushel was assumed to be 0.2 gallon of L.P. Gas. If the interest rate were doubled to 10%, L.P. Gas would have to sell for $0.60/ gallon in order to justify the $1,000 investment.

The question then becomes one of determining the quantity of high temperature solar grain drying equipment that may be purchased for given sets of economic conditions. Under present conditions where concentrating collectors are selling for $25.00/sq. ft., rock at $3.00/ton and 100 degrees of usable heat potential may be stored, L.P. Gas would have to sell for $5.65/gal (as compared to $0.40/gal. today) if high temperature solar drying were to be economically competitive with the solar equipment used only for grain drying. This assumes money to be available at 5%. However, if the collectors could be manufactured for $15.00/ft^2, rock purchased and installed for $1.00/ton, and

*Dunkle, R. V. Randomly Packed Particulate Bed Regenerators and Evaporative Coolers for use in Solar Systems. Proceedings of the Second Southeastern Conference on Applications of Solar Energy, April, 1976. pp. 131, 140.

200 degrees of usable heat potential could be stored, then this system would be competitive with L.P. Gas at $0.85/gal. It would have to be possible to store 400 degrees of usable heat potential with collectors selling for $10.00/sq. ft. and rock for $1.00/ton for high temperature solar grain drying to be competitive at today's prices ($0.48/gal and 5% interest charge on the investment).

In summary, high-temperature solar grain drying cannot economically compete with L.P. Gas at today's prices because L.P. Gas savings do not justify sufficient capital investment, especially at high rates of interest. High-temperature solar grain drying can become competitive under one or a combination of the following conditions, if:

1. LP Gas (or a comparable fuel source) increases significantly in price,

2. Sufficient alternative uses can be found for solar heat besides grain drying so that a portion of the solar equipment cost can be charged to other farm enterprises,

3. Low-interest rate money becomes available for purchase of solar equipment, and

4. Technological achievements can be made to improve collector and storage efficiency and reduce the capital investment required for equipment.

Additional research is necessary if conditions 2 and 4 are to be reached.

SUMMARY:

A focusing, sun-tracking solar collector for heating air to temperatues from 250 to 350 F has been designed, constructed and operated. Thus far the unit has indicated efficiencies from 30 to 50 percent even though the core of the unit has not been so accurately constructed as desired. The output temperatures have ranged from 250 to 320 F.

Essential information for the rational design of rock bed heat storages has been collected for the use of crushed limestone instead of the more costly washed river gravel. It is concluded that the rock should be uniform in size if pressure drop and heat transfer between the air and the rock are to be accurately predicted. In design of a rock storage unit, the heat transfer is improved by choosing the smallest size rock available, but the pressure drop is increased for small size stone. Therefore, the selection of stone size should be as small as can be accommodated for the air flow rate and the depth of the rock bed to achieve reasonable pumping pressure across the bed. Some pressure drop, such as 0.15 inch of water gauge, assist in achieving uniform air flow through the bed, and the smallest rock possible provides the most rapid heat transfer to the stone. The foregoing conditions result in a highly stratified temperature gradient in the bed and, upon reverse flow (for discharging), provide the greatest quantity of heat at the highest temperatures.

Thus, one good design procedure for a rock bed heat storage is to determine the total quantity of storage desired, then select a suitable face area which will provide a depth and velocity of flow resulting in reasonable pumping pressure. Use a uniform size of stone and either loose fill or uniform compaction.

Simulation of high-temperature solar grain drying indicates that the solar system required is not economical today, but the system has the potential of becoming economical in the future if fuel prices advance significantly and/or a major part of the solar system can be charged to more than one farm enterprise.

Table I: Properties of Crushed Limestone

Property	Sample No.	Size: Pass 1/2" Screen Over 3/8" Screen		No. 57 Stone		No. 57 Stone Over 1/2" Hardware Cloth	
		Compacted	Loosefill	Compacted	Loosefill	Compacted	Loosefill
Bulk Density, $\#/ft^3$	1	99.4	86.7	98.5	91.6	93.2	86.1
	2	95.4	88.1	99.3	91.6	98.3	87.1
	Avg	97.4	87.4	98.9	91.6	95.7	86.6
Void Fraction	1	0.383	0.470	0.435	0.461	0.470	0.463
	2	0.449	0.480	0.445	0.454	0.403	0.479
	Avg	0.416	0.475	0.440	0.457	0.436	0.471
Equivalent Spherical Diameter, inches	1	0.35	0.35	0.49	0.50	0.60	0.62
	2	0.37	0.37	0.44	0.45	0.66	0.66
	Avg	0.36		0.47		0.63	

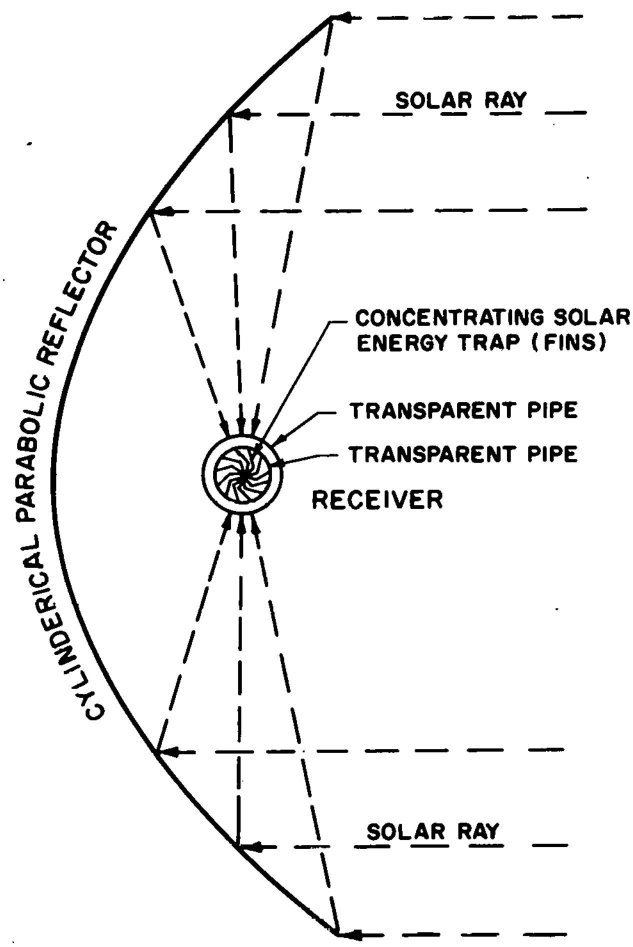

FIG. I. RECEIVER ON FOCAL LINE

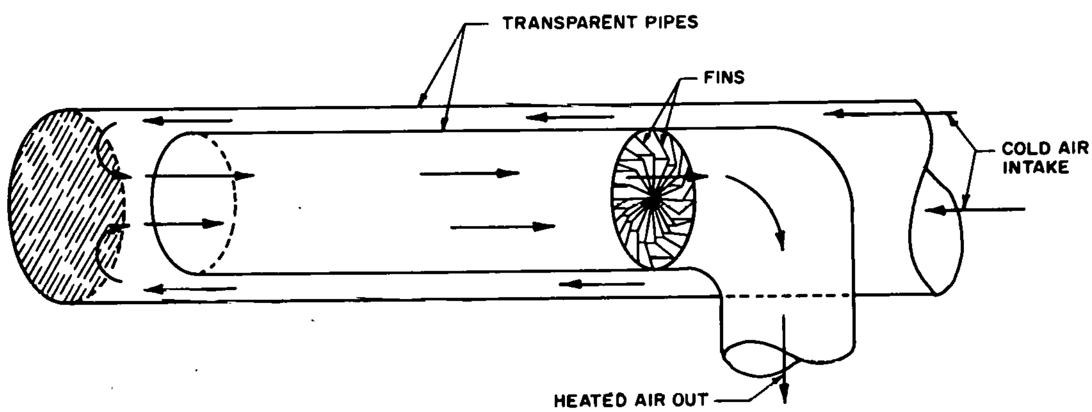

FIG. 2 AIR CIRCULATION THROUGH RECEIVER

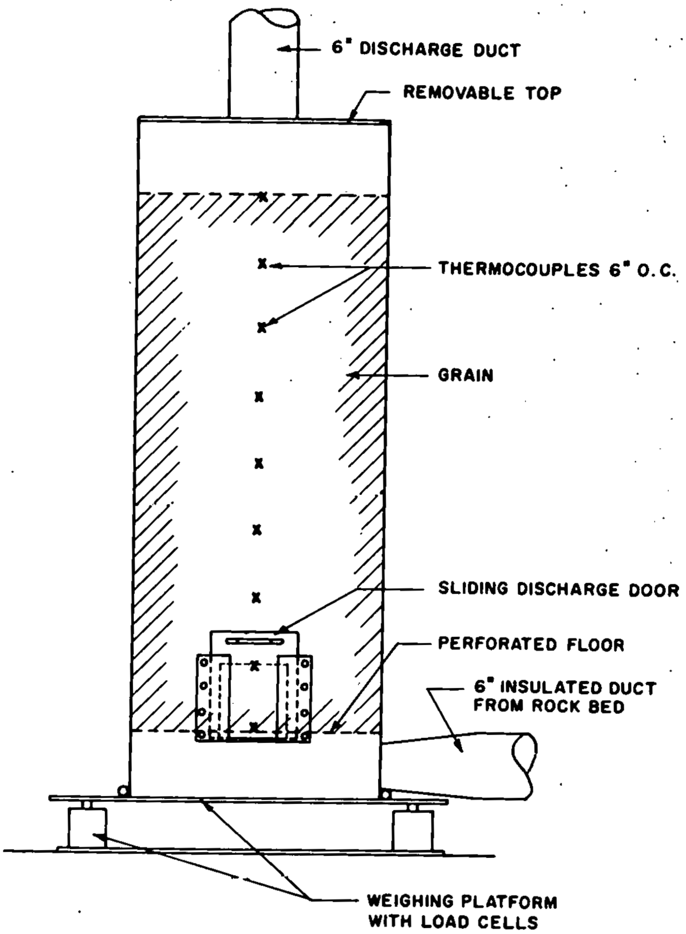

FIG. 4. MODEL SOLAR GRAIN DRYING BIN

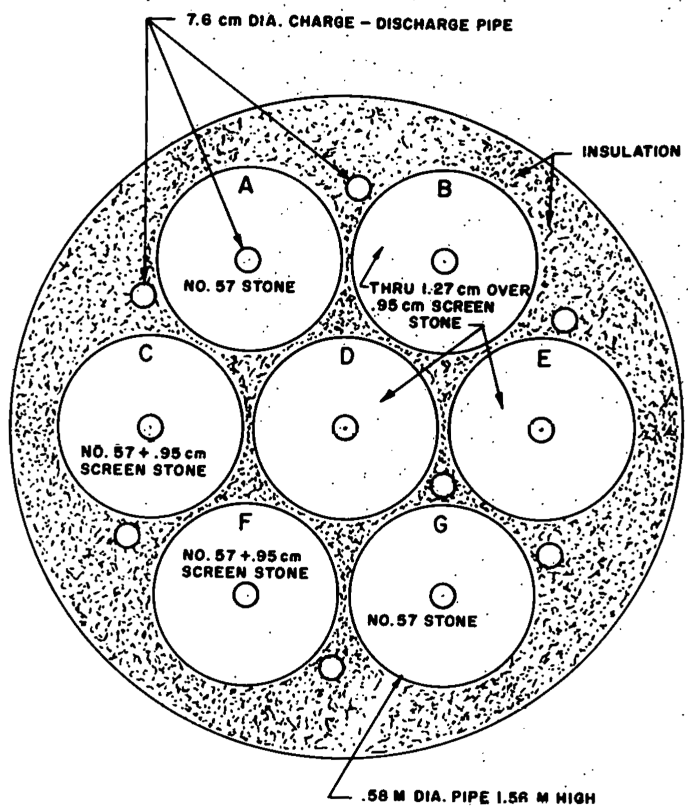

FIG. 3. FOUR TON UNITIZED ROCKBED STORAGE

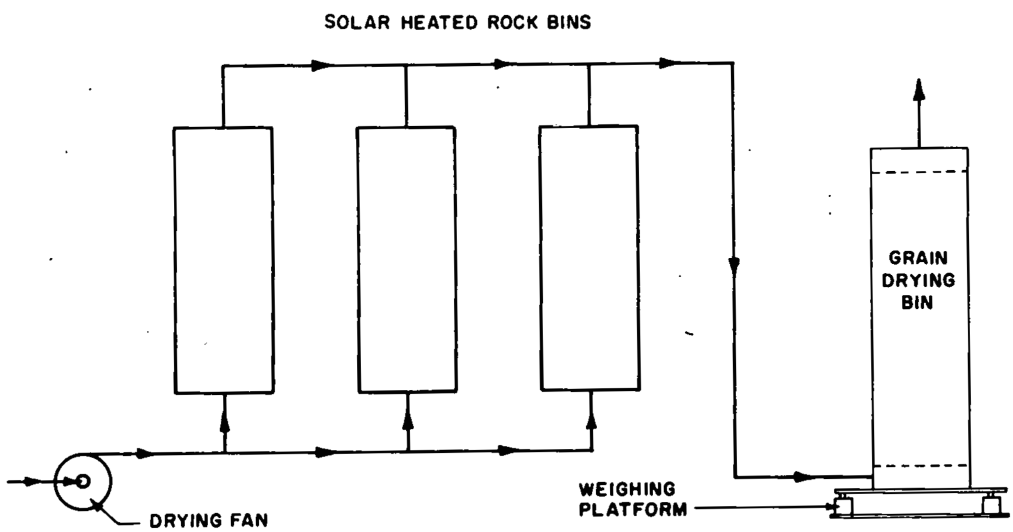

FIG. 5. SCHEMATIC OF SOLAR GRAIN DRYING SYSTEM

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SOLAR REGENERATION OF SILICA GEL AND USE IN GRAIN DRYING

D. F. Aldis[1], R. Burroughs[2] and J. W. Hughes[2]

ABSTRACT

Silica gel was used to store solar energy for drying corn and milo. Three 277 kg lots of silica gel, 26 percent dry basis moisture content, were regenerated with solar energy for two days prior to and during the drying tests.

A 1520 kg lot of corn, 23.5 percent wet basis moisture content and 0.66 m deep, was dried until the moisture content of the surface of the corn in the bin was below 15 percent wet basis with a 40:60 mixture of ambient and desiccated air in 280 hours. A duplicate lot (with a moisture content of 24.2 percent wet basis), dried simultaneously with ambient air alone, required 350 hours. The final average moisture contents of the two lots were 12.0 and 12.5 percent wet basis, respectively. Mold counts and aflatoxin concentrations were significantly lower in corn dried with the mixture of ambient and desiccated air. No significant difference in susceptibility to breakage attributable to drying method was found between the two lots.

Two 1520 kg lots of milo, 18.5 percent wet basis moisture content and 0.53 m deep, were dried with the same airflow rate until the surface moisture content was below 16.2 percent wet basis. Drying required 210 hours with 60:40 mixture of ambient and desiccated air and 330 hours with ambient air. Final average moisture contents were 12.6 percent and 14.4 percent wet basis, respectively.

INTRODUCTION

Historically grain has been left in the field until solar energy reduced the moisture content low enough for safe storage. Picker-sheller combines used today, however, require harvesting corn at high moisture content to minimize field losses, and corn must be dried for safe storage, Brooker et al. (1). Milo also frequently requires artificial drying before storage.

Basic methods of drying grain use high temperature air, ambient (natural) air, or solar-heated air. High temperature drying has been the primary method of grain drying for 20 years. The advantage is short processing time; disadvantages include heat damage and high consumption of fossil fuels. Drying with natural air does not cause heat damage and fossil fuel usage is minimized, but the moisture content of grain in equilibrium with ambient air may be higher than that required for safe storage. In other cases, equilibrium moisture content may be safe for storage, but the time needed to dry grain may be so long that grain quality is reduced. Solar grain drying has advantages of both high temperature and ambient air drying with few disadvantages. The time needed for drying is less than that needed for natural air grain drying, and the grain is not heat damaged. Interest in solar-assisted grain drying has increased rapidly during the last four years.

Drying grain with solar-heated air is satisfactory so long as the sun is shining, but on cloudy days and at night, grain drying is interrupted unless solar energy has been stored. In many locations, ambient air humidity is low enough for drying only during part of the day.

This research was conducted at the U.S. Grain Marketing Research Laboratory, Science and Education Administration, U.S. Department of Agriculture, Manhattan, KS 66502, in cooperation with Department of Chemical Engineering[1] and Grain Science and Industry[2], A.E.S., Kansas State University, Manhattan, KS 66506, Contribution No. 78-340-A.

If solar energy were stored, an active drying front could be maintained throughout the drying process. Solar energy has been stored in various media either as sensible heat or as latent heat of the storage material. MacCracken (10) reviewed the use of phase change material for heat storage. Eckhoff and Okos (5) used dry soil for sensible heat storage, Short et al. (15) used a solar pond, and Hansen and Smith (6) used a rock pile.

The use of solar energy to regenerate silica gel was studied by Koh (9). Silica gel acts as a storage medium for solar energy as drying potential rather than heat. The major advantage for storage of drying potential is that moisture transfer can be controlled more easily than heat transfer. Problems of energy loss to the environment are reduced.

The use of silica gel to control moisture adsorption by grain in humid tropical environments has been studied by Chung and Fleske (2) and by Hsiao (7). Danziger et al. (3) dried corn with air desiccated over a fixed bed of silica gel, and reported that germination of gel-dried corn remained above 90 percent while drying at 60° C (140° F) reduced germination to 80 percent.

Rodda and Rode (12) studied the use of desiccants for drying soybeans. Use of a low temperature, low humidity, desiccant assisted drying system, avoided the thermal stress seed coat cracks associated with loss of germination, and the drying rate was almost the same as that attained by high temperature, low humidity drying. The efficiency of the desiccant assisted drying system was comparable to that of a high temperature drying system.

The feasibility of using desiccants to increase the efficiency of solar grain drying systems was studied by Ko and McCormick (8). After investigating various types of desiccants, they rejected the use of solid desiccants due to the high temperature needed for regeneration. They planned to regenerate liquid desiccants using a high temperature concentrating solar collector.

We employed solar regenerated silica gel in three drying tests: 1) two small lots of corn were dried--one with ambient air and the other with air desiccated by passing through a bed of solar regenerated silica gel; 2) two lots of corn were dried--one with ambient air and one with a mixture of desiccated and ambient air; and 3) two bins of milo were dried by procedures established in the second test.

ANALYSIS OF A DESICCANT ASSISTED GRAIN DRYING SYSTEM

An approximate analysis, similar to that of Treybal (16), was developed to determine the relationships present in a solar-regenerated desiccant drying system. Using the psychometric chart as a base we examined all drying and wetting processes. We assumed that all input temperatures and humidities were constant, that drying and wetting were adiabatic, and that drying and wetting zones were thin compared to the total depth of grain or desiccant. Those assumptions are reasonable for a short time period when inlet temperatures change slowly and drying bins are insulated.

We examined the regeneration of a solid desiccant in a packed bed by plotting equilibrium moisture content of the desiccant versus dry bulb temperature and absolute humidity on the psychrometric chart. The analysis began by considering the increase in sensible heat of the drying air from T_a (ambient temperature) to T_s (temperature of solar heated air) or the regenerator inlet temperature, as shown in Fig. 1a. Because the regeneration process was approximately adiabatic, the condition of the air followed a constant wet bulb line through the desiccant bed until the regenerator (exit) temperature, and absolute humidity (T_r and H_r) were reached. The change in absolute humidity of air across the bed and the airflow rate determined the drying rate. In Fig. 1a, point T_s,H_s (absolute humidity of solar-heated air) lies on the equilibrium moisture content line of the desiccant at the regenerated moisture content ($M_{D,f}$). The point T_r,H_r lies on the equilibrium moisture content line of the desiccant at the moisture content of the gel before regeneration ($M_{D,o}$). This analysis allows one to predict the final moisture content of the regenerated gel, the drying rate, and the air temperature exiting the regenerator bed by measuring the ambient air temperature, relative humidity, original gel moisture content, and the inlet air temperature.

Desiccant wetting can also be analyzed by using the procedure (illustrated in Fig. 1b) described above. The condition of the ambient entering air, T_a, H_a (the absolute humidity of the ambient air) is located on the equilibrium desiccant moisture content line and is the final desiccant moisture content at saturation ($M_{D,f}$). The point T_d, H_d is the exit condition of the air and lies on the original desiccant moisture content line ($M_{D,o}$). As air passes through the desiccant bed the temperature increases from T_a to T_d and the condition of the desiccant will change from $M_{D,o}$ to $M_{D,f}$.

When grain drying is analyzed in the manner described above, the equilibrium moisture content of the grain is plotted on the psychrometric chart, Fig. 1c. The chart will, therefore, contain the air psychrometry, and the equilibrium curves for both silica gel and grain. The changing conditions of air, grain, and desiccant can be observed within the system based on the original grain moisture content, desiccant moisture content, entering air temperature, relative humidity and airflow rate. If the beginning equilibrium moisture content of the grain ($M_{g,o}$) is at point T_g,H_g (temperature of the air leaving the grain and absolute humidity of the air leaving the grain), the desiccant at point T_d,H_d, and the beginning air condition at point T_a,H_a, the following analysis can be made. The air will enter at point T_a,H_a and be desiccated to point T_d,H_d. When the air passes through the grain, it will proceed from point T_d,H_d to point T_g,H_g. The rates of wetting and drying can be predicted by monitoring airflow and changes in absolute humidity across the respective beds of desiccant and grain. In some cases, the large temperature difference between the temperature of desiccated air (T_d) and the ambient air temperature (T_a) will result in heat loss from the desiccated air through air ducts to ambient air. That situation is shown in Fig. 1c by points T_d', H_d' and T_g', H_g'. When the desiccant air loses sensible heat to the ambient air, the desiccated air temperature shifts from T_d to T_d'. The air condition changes as it passes through the corn from point $T_d'H_d'$ to point $T_g'H_g'$, where $T_g'H_g''$ are in equilibrium with the original grain moisture content. The analysis indicates that the surface grain temperature of a desiccant grain drying system will be equal to or less than the grain temperature of a natural grain drying system.

Dry air from the regenerated desiccant bed can be adjusted to a desired relative humidity by introducing ambient air so that grain moisture content can be regulated. The resulting air condition will be located on the wet bulb line between the ambient and desiccated air conditions as shown in Fig. 1d. The ratio of the flow rate of desiccated air to the total flow rate of desiccated plus ambient air is equal to the ratio of the length of the line from point T_m,H_m, to point T_a,H_a over the length of the line from point T_a,H_a to point T_d,H_d.

MATERIALS, EQUIPMENT AND METHODS

Three solar collector-silica gel storage units described by Koh (9) were used for solar regeneration of silica gel (Fig. 2). Each unit consisted of a 93 W (1/8) hp fan, a suspended flat plate collector, 1.2 m by 2.4 m (4 ft x 8 ft), and a 0.762 m (30 in.) diameter steel bin containing 75.4 kg (166 pounds), 0.178 m (7 in.) deep bed, of silica gel of 26 percent dry basis moisture content. The gel in each unit was dried on two sunny days (8 hours per day) before each test. On sunny days during the tests, the units not being used to dessicate air were regenerated so that dried gel was available to desiccate air when the gel became wet.

The first test, conducted during May, 1977, at Manhattan, Kansas, used corn harvested the fall of 1976 and stored in a cold room (5° C). One day before the test began, the corn was sealed in small drying bins (0.75 m diameter) and allowed to equilibrate thermally with the ambient temperature. One lot, 752 kg (6 bu) of corn, 16.4 percent wet basis moisture content, was dried with air that had been passed through a fixed bed of solar regenerated silica gel at a flow rate of 1.1 m^3/min (40 cfm, and 6.7 cfm/bu). A second lot was dried with natural (ambient) air using the same airflow rate.

The grain used in the second test was combined in early September, 1977, and was left in the truck for 24 hours before the test began. The first of two 2 m (6 ft) diameter bins was filled to a depth of 0.64 m (25.5 in.) with 1520 kg (60 bu) of corn with 23.5 percent wet basis moisture content. The grain was dried with an airflow rate of 4.4 m^3/min (155 cfm, 2.6 cfm/bu) with a mixture of ambient and desiccated air as shown in Fig. 3. When ambient relative humidity was above 60 percent, the ratio of desiccated air to ambient air entering the bin was set at 60:40. Ambient air alone was used to continue the drying process at relative humidities below 60 percent. The second bin, containing 1520 kg (60 bu) of corn with 24.2 percent wet basis moisture content, was dried with natural (ambient) air at the same flow rate.

Susceptibility to breakage of corn in test 2 was measured with procedures developed by McGinty (11) and Stephens and Foster (16). A 100-gram sample was placed in the Stein breakage tester, and the tester was operated for 4 minutes. The weight-fraction of material remaining on a 12/64 in. standard screen, after being shaken 30 strokes on a Gamet shaker, was recorded as the breakage index.

Fungal invasion in test 2 was examined by plating surface-disinfected seeds on malt agar containing 4 percent sodium chloride and 200 ppm tergitol. Unbroken seeds were disinfected by washing for one minute in 5.25 percent sodium hypochlorite (Clorox brand) followed by two sterile water rinses. Petri plates were incubated 5-7 days at 25° C and the fungi identified. Aflatoxin concentration was determined by thin-layer chromatography using the method of Seitz and Mohr (13).

Two lots of milo were dried in the third test begun in early November, 1977. The first bin, containing 1520 kg (60 bu) of 18.5 percent wet basis moisture content, received an airflow rate maintained at a constant volumetric flow rate of 3.68 m^3/min (130 cfm, 2.2 cfm/bu). As in test 2, desiccated air was added to the drying system when the relative humidity was above 60 percent at a ratio of desiccated air to ambient air of 40:60. The second bin utilized ambient air alone to dry the same quantity of grain (with an original moisture content of 18.3 percent) at the same airflow rate.

Grain was sampled by probing at five evenly spaced locations, and probed samples were pooled for each depth. Samples were collected every second or third day during a test period for moisture contents determination. Grain moisture contents were determined by drying approximately 60 g samples in a forced air oven at 103° C (217° F) for 72 hours.

Airflow rates through the grain beds were determined by measuring the pressure drop with an inclined manometer and using the curves of Shedd (14). A vane anemometer placed at the top surface was used to measure airflow. The two methods gave similar results.

Hygrothermographs were placed at various positions in the drying systems to record air temperature and relative humidity.

RESULTS AND DISCUSSION

Results of the first test are summarized in Fig. 4. The time required to dry grain in the bin with desiccated air was less than that required with ambient air and the moisture content was significantly lower. To prevent overdrying (moisture content < 12 percent) the airflow rate in the solar collector could be increased to lower the regeneration temperature, thus increasing the moisture content of the regenerated desiccant and decreasing its energy storage capacity. Another approach would be to mix ambient air with the desiccated air stream before passing the air mixture through the grain.

In the second drying test, a mixture of 40 percent ambient air was mixed with desiccated air. In addition the ambient desiccant air mixture was only used during times of high relative humidity (above 60 percent r.h.). In Fig. 5 the inlet temperatures of the naturally dried bin and the desiccant assisted bin are shown over the drying period. The temperature of the air entering the desiccant assisted dried corn was generally higher than the ambient air temperature but when the desiccant was not used the air temperatures of both bins were generally the same. The inlet relative humidities of the two bins are plotted versus time in Fig. 6.

The temperature of air exiting the corn bins is plotted vs time in Fig. 7. Although the entering air temperature of the desiccant assisted bin is higher than that of the naturally dried bin, the exiting temperature of the desiccant assisted air dried corn bin is slightly lower than that of the exiting natural air. The decrease in temperature is explained by a sensible heat loss from the desiccated air as illustrated in Fig. 1c. The relative humidity of the air leaving the corn is plotted in Fig. 8. The relative humidity values are nearly equal and approximately constant over much of the drying period. The grain moisture contents of the corn on the surface and at various depths are plotted vs time (Fig. 9) for both the natural air dried corn and the desiccant assisted dried corn. The times needed for the moisture content of the corn at the surface to reach 15 percent wet basis for the desiccant assisted dried corn and the naturally dried corn were 280 hours and 350 hours, respectively. The final moisture content of the naturally dried corn was 1.6 percent higher than the final moisture content of the desiccant assisted air dried corn.

During the second test portions of the probe-samples used for moisture content determination were examined for fungal invasion. At the beginning of the drying test, corn kernels were invaded by *Fusarium* (44%), *Penicillium* (27%), *Rhizopus* (20%), *Aspergillus flavus* (12%), and *A. niger* (15%). When the grain was dry, there was little difference in fungal invasion of grain dried with desiccant air or with natural air. The bottom two layers, however, had less total invasion than the upper surfaces. *Penicillium* and *A. niger* increased more than did other fungi. *A. flavus* invasion increased to an average of 38 percent of the intact kernels in both bins and varied from 31 percent at the bottom to 42 percent at the surface. The aflatoxin B_1 accumulated in each layer (Table 4) reflects the length of time that conditions were suitable for toxin production. The average aflatoxin concentration for the desiccant assisted dried corn was 13 ppb and for naturally dried, 37 ppb. Shorter drying times and lower in bin temperature produced grain with aflatoxin contamination below the FDA established guide level of 20 ppb B_1 for corn in market channels (4).

Breakage-index measurements were made at the end of the second test. The breakage index of the corn was lower for desiccant assisted drying than natural drying, but the final moisture content was also lower (Table 2). To identify the relative effects of the drying method and moisture content, breakage-index was plotted versus moisture content (Fig. 10). The curves obtained for natural-air dried (C_n, with r^2 values of 0.85) and natural-air dried plus desiccant assisted-dried corn (C_{n+d}, with r^2 value of 0.86) versus moisture content, are plotted in Fig. 10. Analysis showed no significant difference between the least squares slope and intercept for C_n and C_{n+d} at the 95 percent confidence level. The difference in kernel breakage between drying treatments was attributed to the lower moisture content achieved with desiccant assisted drying.

Energy consumption for corn dried in the second test is presented in Table 3. Electrical energy used to drive the solar regenerator-silica gel storage unit fans was greater than the energy saved by reducing drying time.

In the third test, milo was dried with a mixture of desiccated and ambient air and with natural air. Only 40 percent of the drying air passed through the desiccant before entering the milo. As in the corn drying experiment, desiccated air was used only during periods of high humidity. Figure 11 illustrates the relation between the moisture contents in both bins and drying time. The original moisture content of the milo was 18.5 percent. The drying period was long enough for the drying zone to pass completely through the natural air dried bin. To determine relative drying periods, the times it took for the surface moisture content to decrease to 16.2 percent wet basis moisture content in both bins were taken as drying times.

The total energy used for drying both bins of milo is presented in Table 4. The total energy is less for the desiccated assisted milo drying air. This differs from the result obtained for the second test although the reduction in energy is reasonably small.

CONCLUSION

Use of solar regenerated silica gel for desiccating air used for drying grain decreased drying time substantially for corn and milo. The energy savings with this method over natural air drying were small due to fan electrical energy used to dry the desiccant and to remove the energy (drying potential) stored in the gel. Mold growth was decreased when desiccant dried air was used. The susceptibility to corn breakage appeared to be unaffected by use of the desiccant, but appears to be a function of moisture content.

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Table 1. Aflatoxin B_1 in corn dried with 60:40 mixture of desiccated air and ambient air compared with natural air. Drying times were 250 and 350 hours, respectively

Distance from grain surface (m)	Aflatoxin B_1 (ppb) Desiccant assisted drying	Natural drying
0.64	None detected	None detected
0.51	None detected	15
0.39	8	16
0.26	17	60
0.14	40	94

Table 2. Final moisture contents and breakage-index of corn dried with a 60:40 mixture of desiccated and ambient air compared with natural air

Distance from grain surface (m)	Desiccant assisted drying		Natural drying	
	Moisture content (% w.b.)	Breakage index[1]	Moisture content (% w.b.)	Breakage index[1]
0.64	11.1	89.2	11.7	89.7
0.51	11.3	88.7	12.0	91.8
0.39	11.3	90.3	12.4	91.9
0.26	11.2	90.5	13.0	92.6
0.14	11.8	90.2	13.4	93.6

[1]Weight-fraction remaining on 12/64" screen after 4 min. in Stein breakage tester.

Table 3. Comparison of electrical energy consumption for drying 0.64 m depth and 2 m diameter of 23-24 percent w.b. moisture content corn to below 15 percent w.b. moisture content using a 60:40 mixture of desiccated and ambient air (desiccant assisted) and ambient air alone (natural)

Drying method	Time (hr)	Energy (kWhr)
Desiccant assisted		
Gel regeneration (93 W motor)	85	7.9
Gel wetting (93 W motor)	146	13.6
Grain drying (214 W motor)	280	60.0
Total energy		81.5
Energy/kg water removed	0.10 kWhr/kg	
Natural		
Grain drying (214 W motor)	350	74.9
Energy/kg water removed	0.09 kWhr/kg	

Table 4. Comparison of electrical energy consumption for drying 0.64 m depth of 18 percent w.b. moisture content milo to below 15 percent w.b. moisture content using a 40:60 mixture of desiccated and ambient air (desiccant assisted) and ambient air alone (natural)

Drying method	Time (hr)	Energy (kWhr)
Desiccant assisted		
Gel regeneration (93 W motor)	75	7.0
Gel wetting (93 W motor)	93	8.6
Grain drying (214 W motor)	210	44.9
Total energy		60.5
Energy/kg water removed	0.18 kWhr/kg	
Natural		
Grain drying (214 W motor)	330	70.6
Energy/kg water removed	0.22 kWhr/kg	

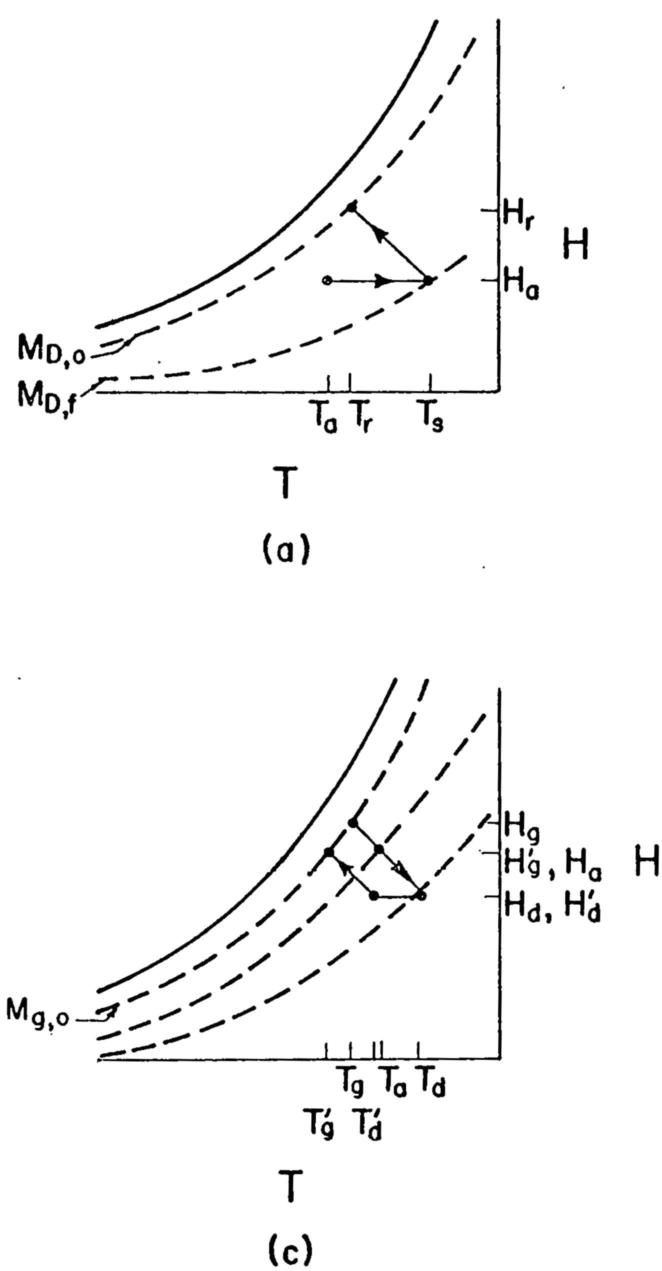

Fig. 1. Representation of (a) solar regeneration of a desiccant, (b) wetting of a desiccant, (c) effect of sensible heat loss on desiccant assisted drying, (d) graphical determination of the condition of a mixture of ambient air and desiccated air.

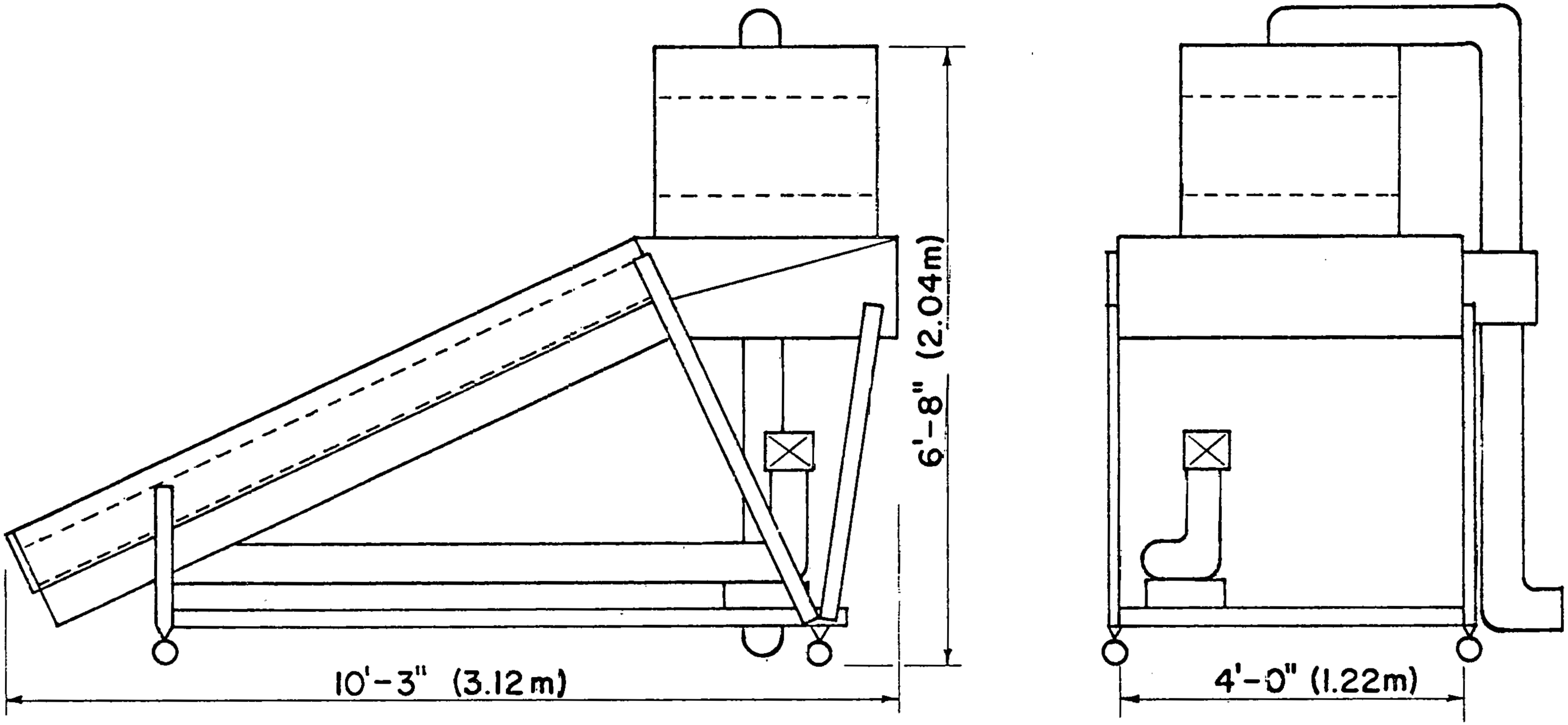

Fig. 2. Schematic diagram of flat-plate solar collector-silica gel bin unit.

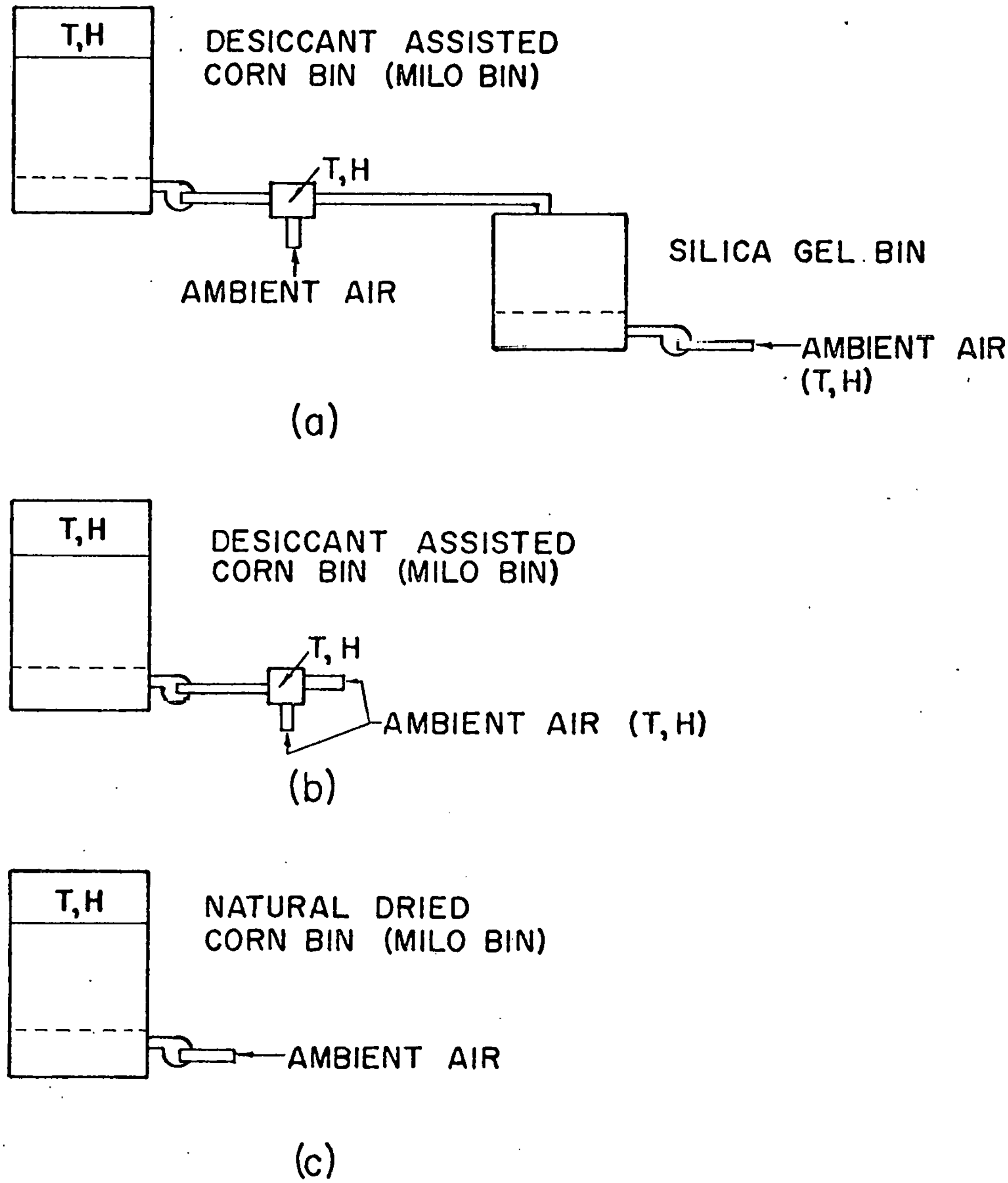

Fig. 3. Schematics of drying systems used in tests 2 and 3, (a) desiccant assisted with desiccant in use, (b) desiccant assisted with desiccant not in use, (c) natural drying system. The symbols T and H correspond to the points in the system where temperature and relative humidity were used.

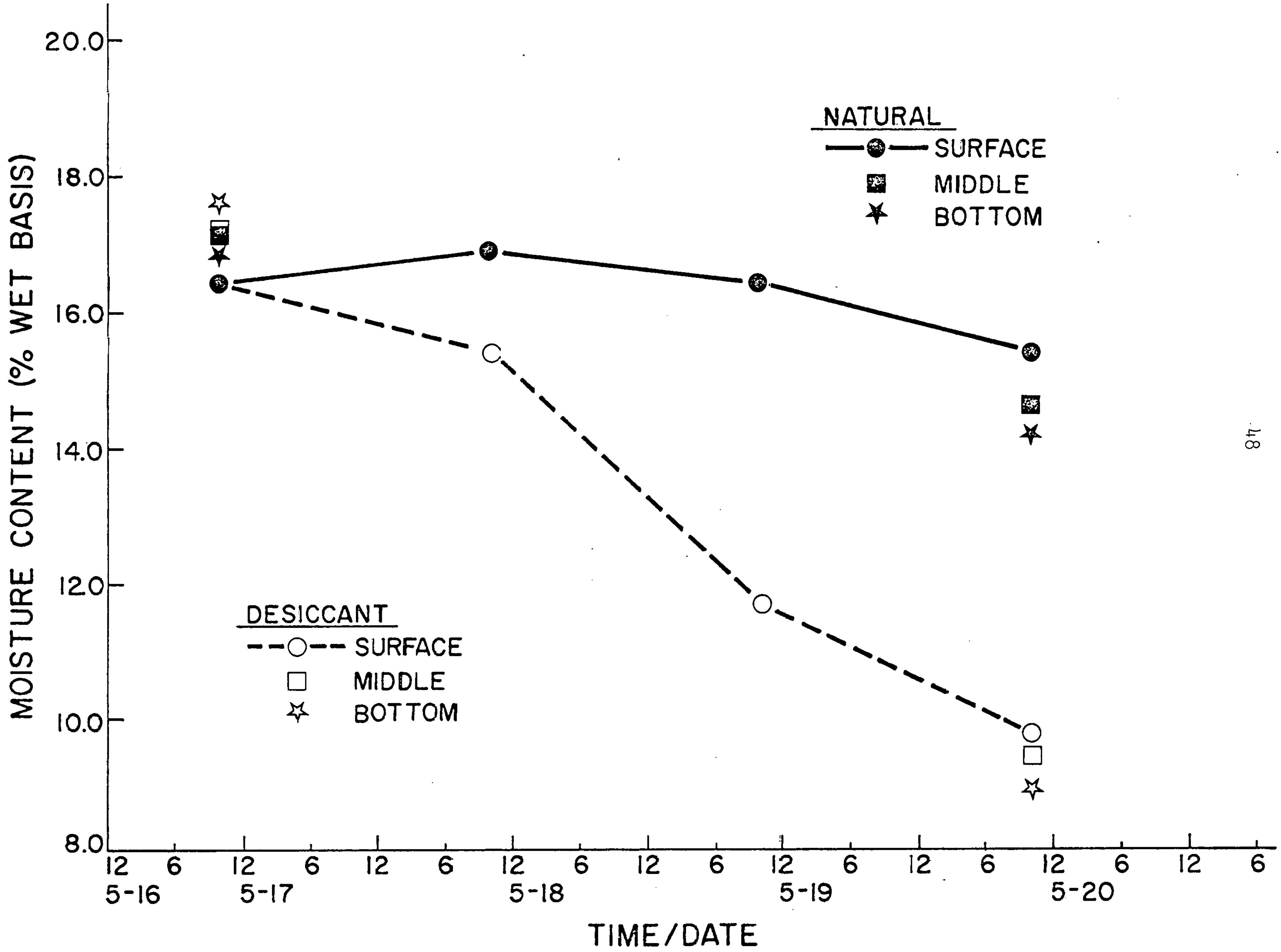

Fig. 4. Moisture content of corn in the first test vs time at various depths.

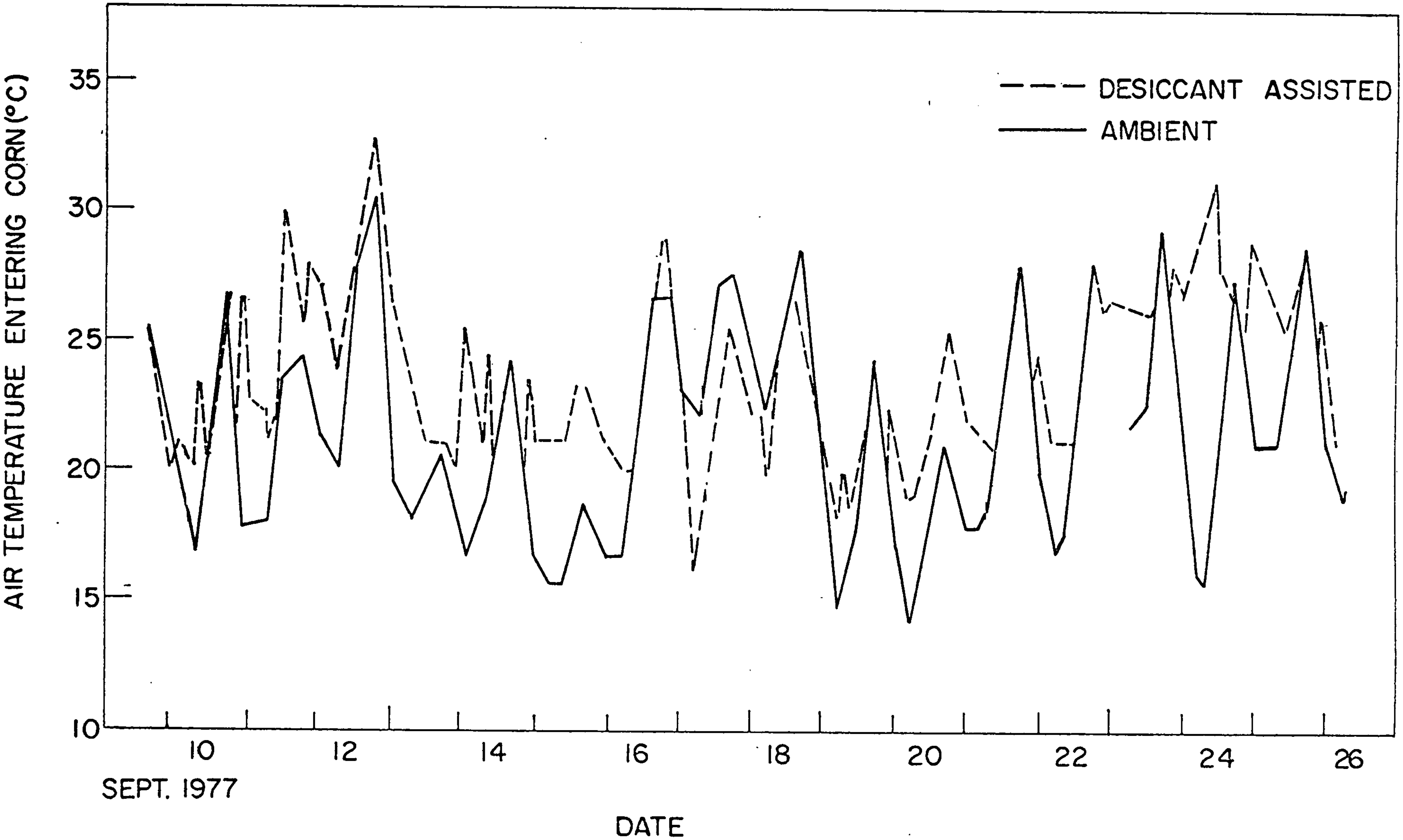

Fig. 5. Air temperature entering desiccant assisted corn bin, natural (ambient) corn bin, and ambient air in test 2.

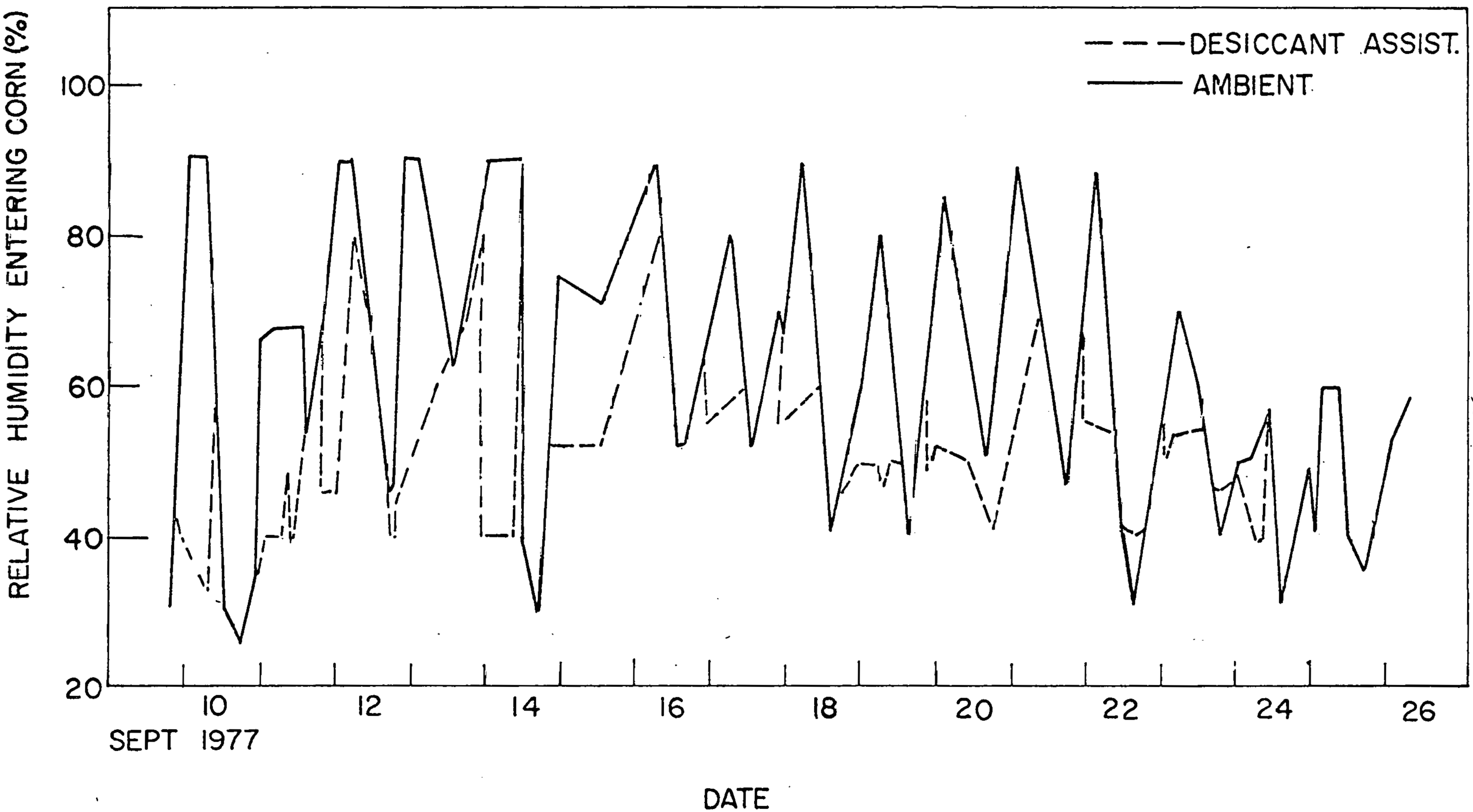

Fig. 6. Relative humidity of air entering the desiccant assisted corn bin, natural corn bin, and the ambient air in test 2

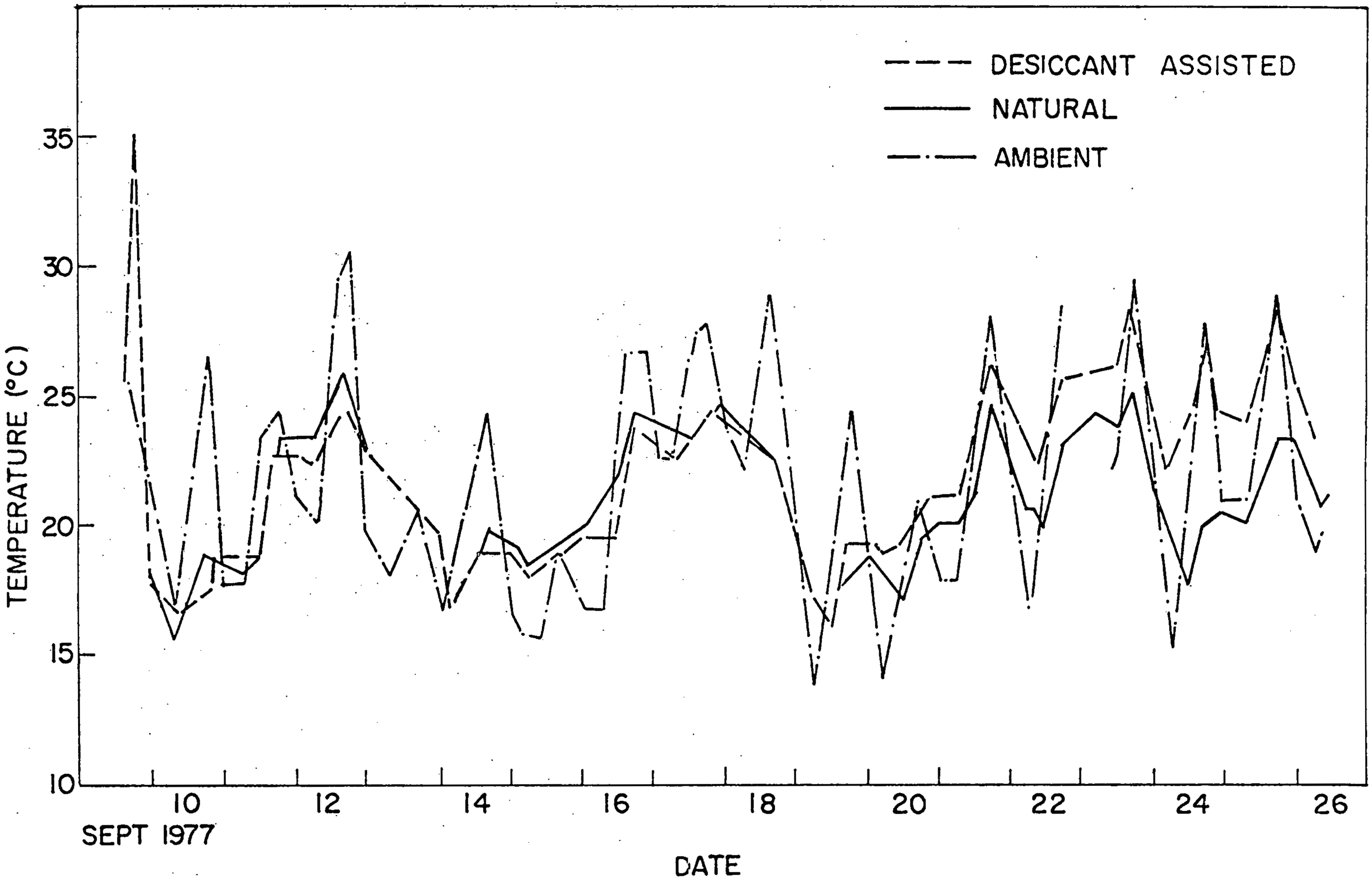

Fig. 7. The air temperature leaving the desiccant assisted corn bin, natural corn bin, and ambient air in test 2.

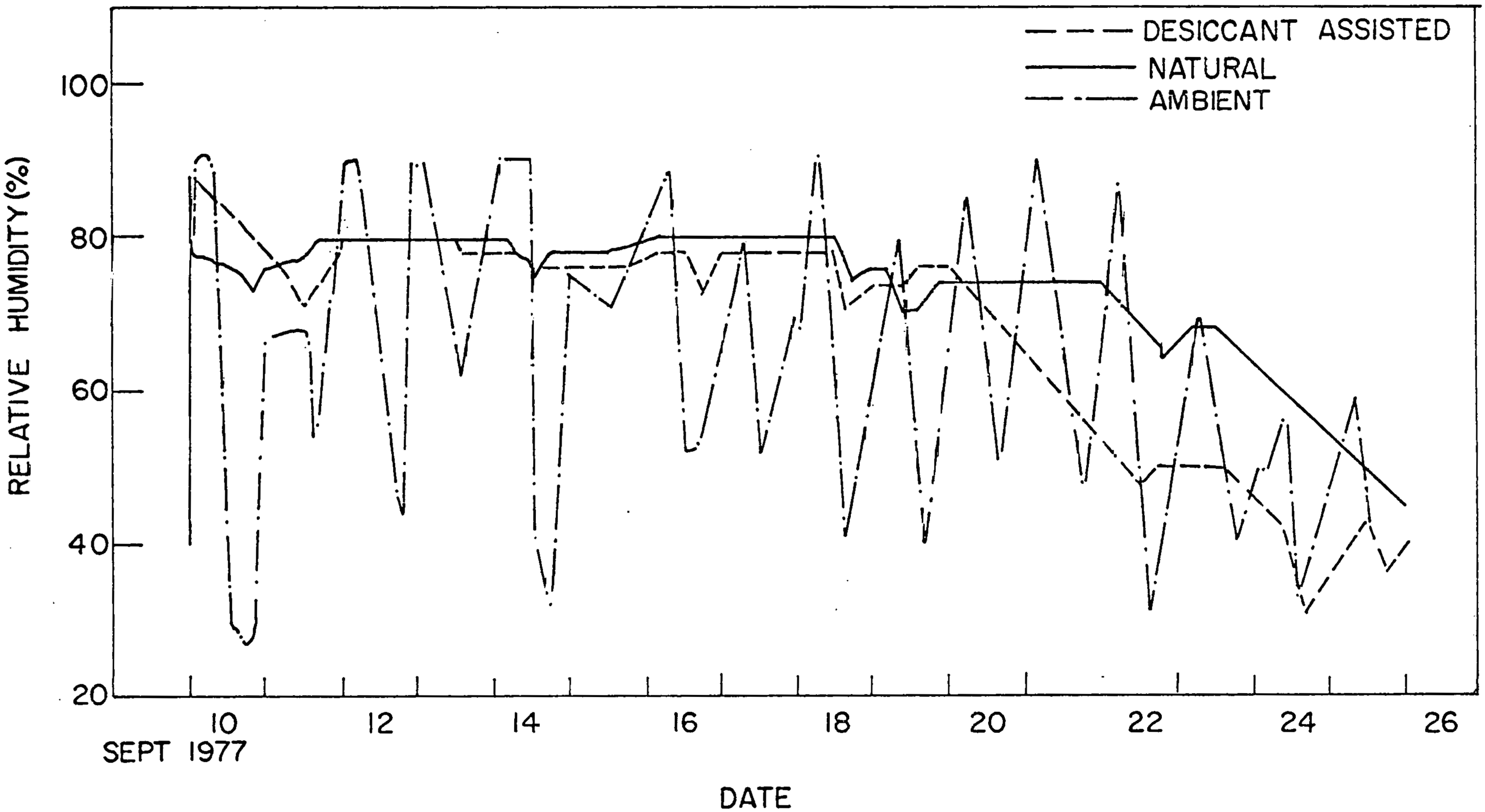

Fig. 8. Relative humidity of the air leaving the desiccant assisted dried corn, leaving the naturally dried corn, and of ambient air in test 2.

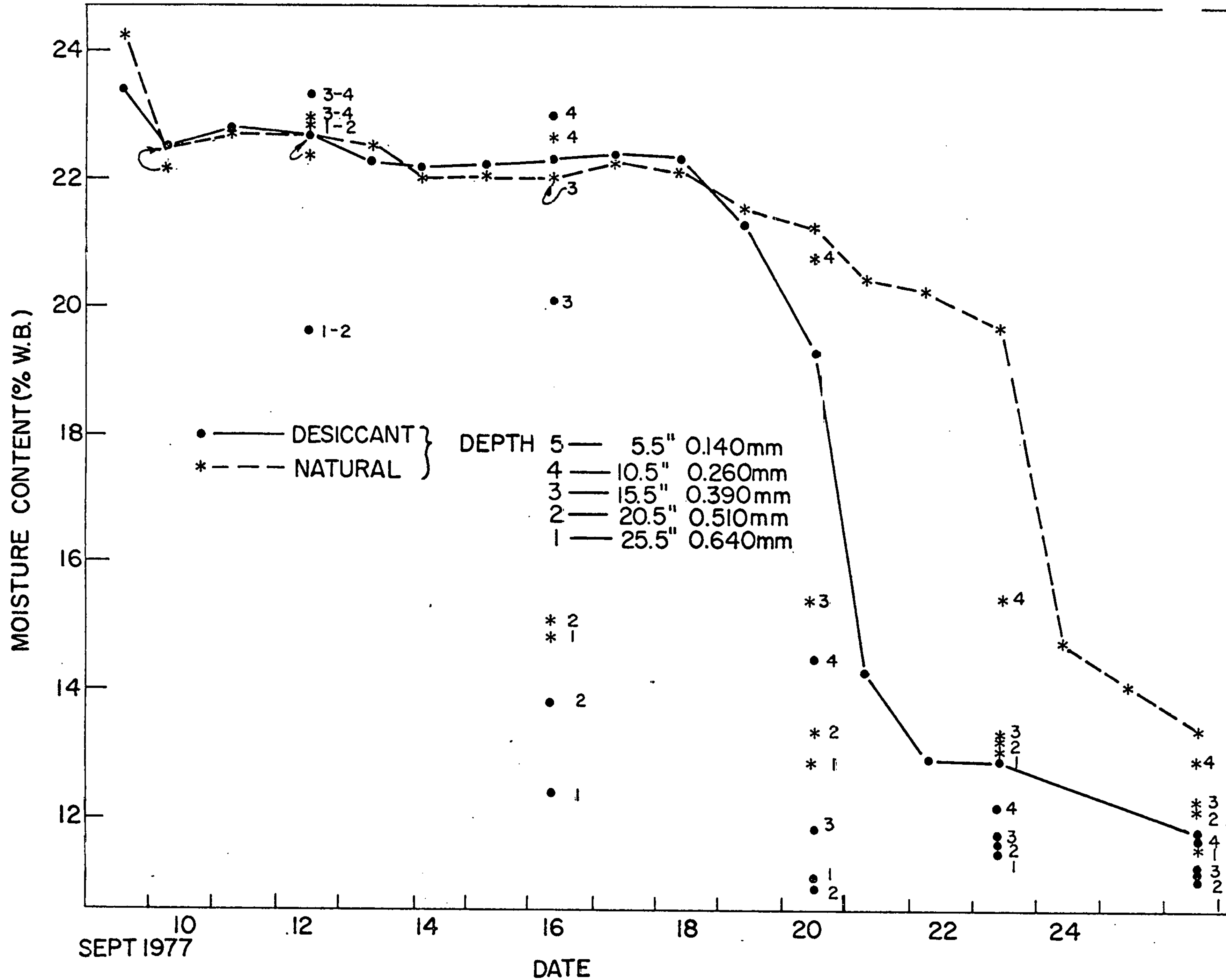

Fig. 9. The moisture content vs time, depth of the corn, and drying method in test 2.

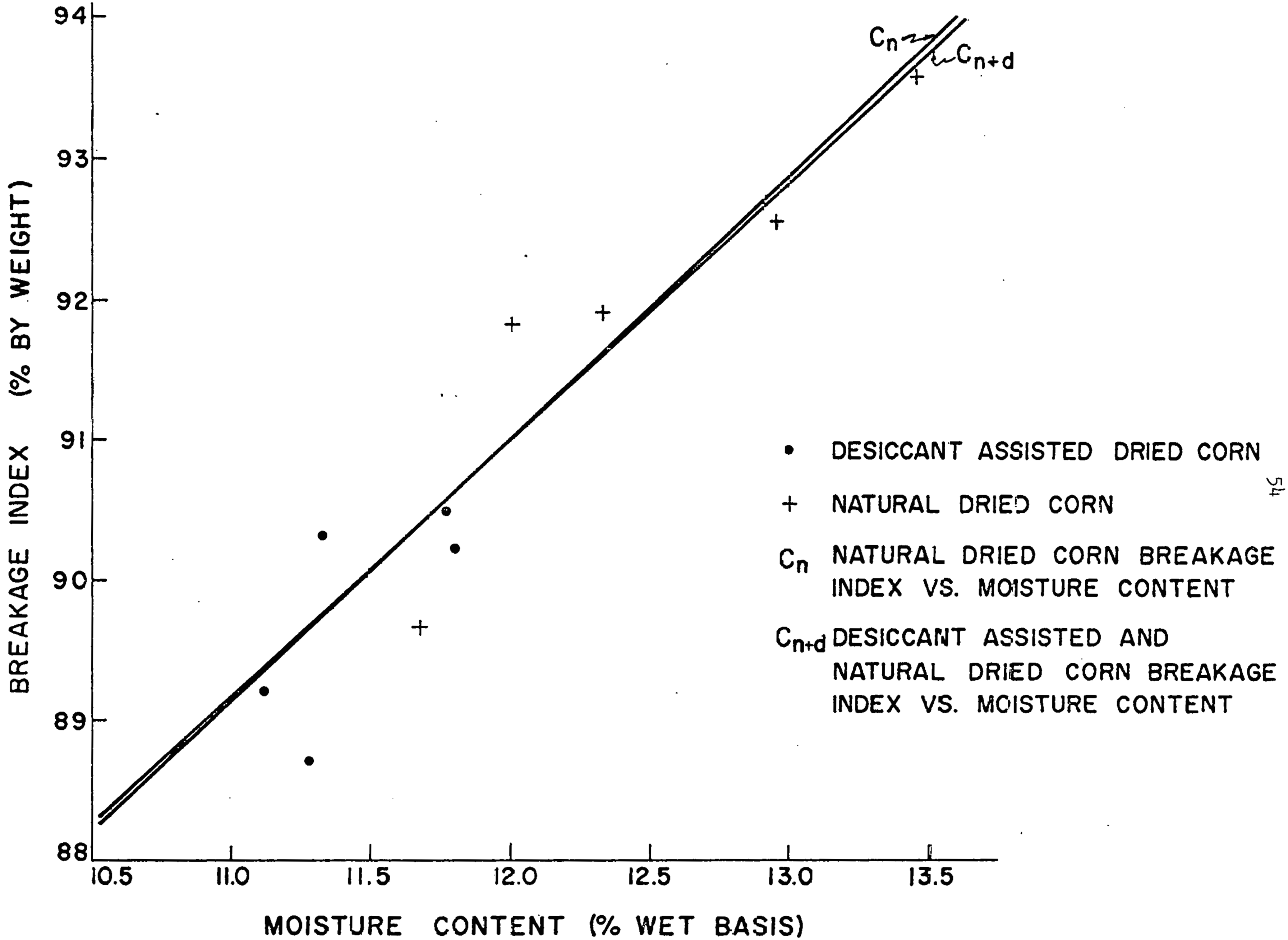

Fig. 10. Effect of moisture content and drying method on breakage susceptibility.

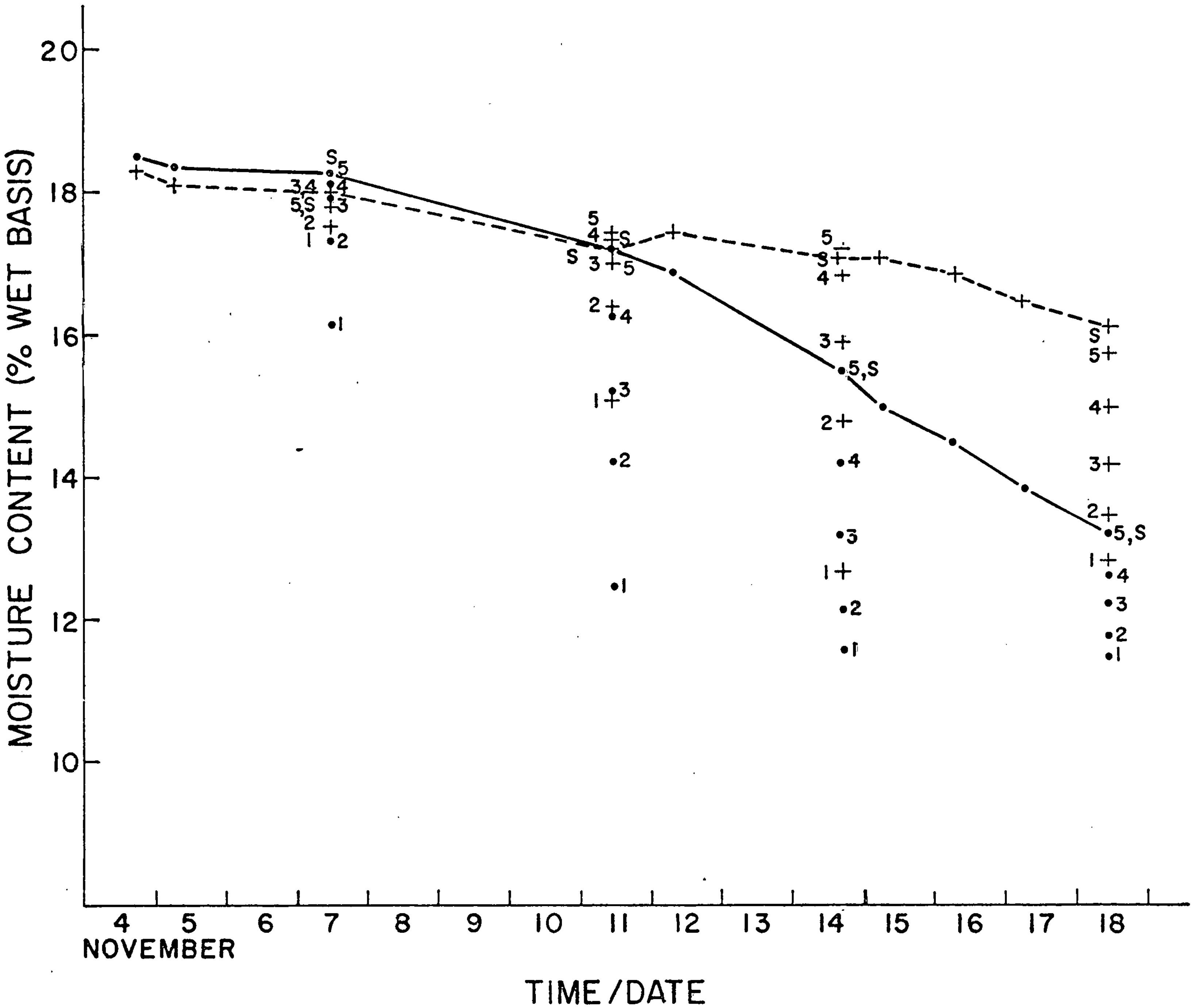

Fig. 11. Moisture content of milo in the third test vs time at various depths.

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SOLAR CORN DRYING WITH A COMBINATION DESICCANT/LOW-TEMPERATURE SYSTEM[1]

Carl J. Bern, Michael E. Anderson, and W. F. Wilcke[2]

INTRODUCTION

The annual use period of a solar collector on a conventional low-temperature drying system is typically 30 to 60 days. If the collector is not used for another purpose, it is idle for the rest of the year. This paper reports results of a field study of a system that prolongs the use period of the solar collector to as long as 6 months and stores solar heat in the form of drying capacity in overdried corn. Heat from a solar collector is used to overdry corn for later use as a desiccant to be mixed with wet corn at harvest.

REVIEW OF LITERATURE

White and Ross (1971) found that, when wet and dry corn are blended and held at 40°F without aeration or further disturbance, the fractions will, within about 10 days, come to moisture contents that differ by about 3 percentage points. Neither fraction reaches the average moisture content. Hart (1967) reported similar results. Effects of mixing and aeration on the rate and extent of the moisture-content change were not found in the literature.

Morey et al., 1976, showed that a system that dries wet corn to 20 or 21% moisture by using a high-temperature LP dryer and then completes drying to about 15% moisture by using a low-temperature dryer in most instances reduces total drying energy use from the quantity required if all drying is done in the LP dryer.

Drying over the 20 to 15% moisture range can be done slowly because the 20% moisture corn has a long allowable storage time (about 55 days, assuming a corn temperature of 48°F, U.S. Dept. Agric., 1968). Thompson (1977) determined by computer simulation that, for 24 years of 28 years studied, 20% moisture corn at Des Moines, Iowa, harvested Oct. 15 can be dried to 15% moisture with less than 0.5% dry-matter loss by using an aeration rate of 0.5 CFM/BU and atmospheric air heated 2°F by the fan.

Experimental

System management followed these steps:

- During summer, corn was overdried by using heat from a solar collector.
- At harvest, desiccant (overdried) corn was mixed with wet corn to give an average moisture content of 20.8%.
- The mixture was low-temperature dried at a low airflow rate.

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The field test was carried out using two 18-ft diameter bins at the Woodruff Farm (Figure 1). Performance of the combination system was compared with that of a conventional low-temperature drying system.

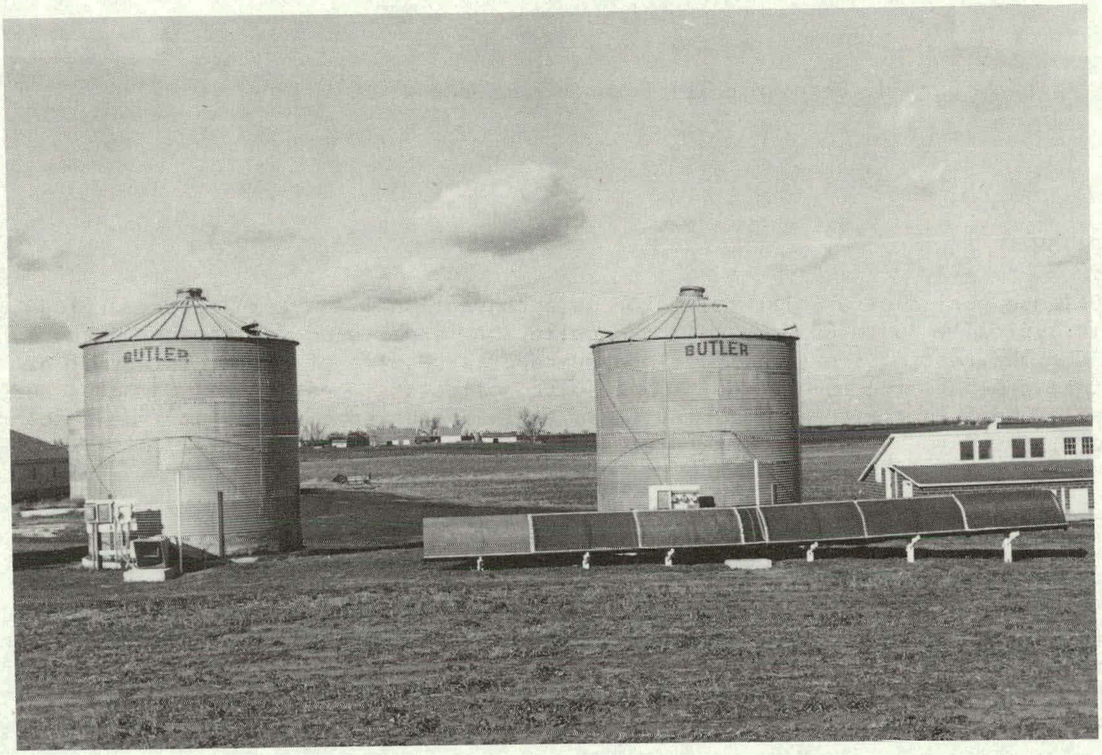

Figure 1. Control bin (left) and desiccant/low-temperature bin (right) at Iowa State University, Woodruff Farm, southwest of Ames.

The solar collector was constructed following a design by Kline (1977). Specifications are shown in Table 1.

Table 1. Solar collector specifications

Type:	Fixed, covered, suspended plate, air
Width:	4 ft
Area:	192 ft^2
Cover Material:	Greenhouse fiberglass
Suspended plate material:	1/4-inch chipboard
Mounting angle:	Summer 30° Fall 45°
Airflow:	Summer 1650 CFM Fall 2450 CFM
Temperature rise (max):	Summer 12.0 °C Fall 8.2 °C
Cost:	0.3 HR/ft^2 labor 1.59 \$/ft^2 materials

On Aug. 1, 1977, 805 BU* of corn was cleaned and placed in the east bin for use as a desiccant. Table 2 shows specifications of the desiccant preparation procedure. A late start and unfavorable August weather limited moisture removal from the desiccant.

Table 2. Specifications of desiccant preparation procedure

Date started:	Aug. 1, 1977
Initial moisture content:	13.0%
Final moisture content:	11.7%
Quantity of corn:	805 BU
Fan:	1/3 HP axial-flow, 463W
Controls:	Fan on when sun shining and ambient relative humidity less than 55%.
Aeration rate:	2.0 CFM/BU
Total fan time:	112 hours (over a period of 51 days)
kWh/BU/% pt:	0.048

Bin filling was begun on Oct. 11, 1977. Wet corn was placed on top of the desiccant corn in the desiccant bin. Desiccant corn and wet corn were mixed by using a single-auger grain-stirring system installed in the bin. The control bin was filled to the same depth with wet corn. Drying in the control bin was completed Nov. 25, 1977, and resumed in April 1978. Drying was completed May 15, 1978. No spoilage of corn occurred in either bin. Table 3 shows the operating schedule and a summary of results.

Electrical energy use and electrical demand for the combination system were much lower than for the conventional system (0.15 vs. 0.35 kWh/BU/% pt and 0.8 vs. 2.74 kW/1000/BU, respectively). However, use of the combination system would necessitate storage of corn amounting to about 20% of the bin volume for use as a desiccant and the purchase of a stirring system and a solar collector. Corn damage from stirrer operation has not yet been evaluated. A second field test and an economic analysis of the system are planned.

Water removal from the desiccant corn during summer seems to be a very energy-efficient process. It could be used with other management procedures. For example, corn in storage over summer could be overdried and blended with wet corn in the fall. The moisture content of this blend could be adjusted to an optimum level for sale or storage as well as to a level appropriate for low-temperature drying as was done in this field test.

SUMMARY AND CONCLUSIONS

A field test was carried out comparing corn drying in a combination desiccant/low-temperature system with drying in a conventional low-temperature system. The combination system uses corn overdried with heat from a solar collector as a desiccant. Drying was completed without spoilage in either bin. Based on one year's results, it can be concluded that a combination desiccant/low-temperature system can dry corn with significantly less electrical energy than a conventional low-temperature system.

*1 BU = 47.32 lb dry matter.

Table 3. Operating schedule and summary of results.

	Desiccant Bin	Control Bin
	Fan: 1-HP axial-flow	5-HP axial-flow
Aeration Rate:	0.79 CFM/BU (Based on total BU in bin)	1.7 CFM/BU
Fan Operation:	Continuous	Continuous
Stirrer:	1.5 HP, single-auger	None
Stirrer Operation:	15 days continuous, then 8:00 AM-4:30 PM during fan operation	——
Heater:	None	2.4 kW
Heater Operation:	——	Continuous
Date Filled:	Oct. 11-14, 1977	Oct. 11-14, 1977
Initial Moisture:	Desiccant: 11.7% Wet : 23.3% Combined : 20.8%	23.1%
Days Operation:	87 days	41 days
Final Moisture:	14.7%	15.3%
Fan Energy (desiccant preparation):	52 kWh	——
Fan Energy, fall & spring:	1954 kWh	6232 kWh
Stirrer Energy:	873 kWh	——
Heater Energy	——	2341 kWh
	2879 kWh	8573 kWh
kWh/Bu/% pt	0.15 (BU added in fall)	0.35
Maximum electrical demand kW per 1000 bu:	0.8 (BU added in fall)	2.74

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HARVESTING AND DRYING HIGH MOISTURE WHEAT

J.R. Barrett, S.D. Parsons and B.A. McKenzie [1]

Wheat can be successfully harvested at moisture contents up to 24-25% with present day equipment. At the same time virtually all grain drying systems are adaptable for wheat drying. Bin drying methods are especially well adapted. The potential benefits of early harvest of high moisture wheat and drying cannot be disregarded, especially if double-crop soybeans following wheat is being considered, or currently used.

Harvesting high-moisture wheat can move the harvest date ahead 5-7 days or more. This can be especially important for double-crop soybeans since each day of earlier planting can mean 1/2 to 1 bu/a more yield. Earlier harvesting results from not having to wait for natural in-field dry-down, and from being able to harvest sooner after rainy or foggy weather. Also, fewer calendar days should be needed for harvest since combining can begin in early morning while the dew is still present, and can extend to late evening when the humidity is high.

Early wheat harvest should also mean higher wheat yields due to reduced shatter loss at the combine header. The early-harvested wheat will also usually be of better quality than the same wheat harvested later. Once the grain has reached a dry condition while standing in the field, any re-wetting due to morning dews or rainy conditions will consistently reduce grain quality. Early harvest coupled with drying offers one of the best opportunities to maintain top grain quality.

High-moisture harvesting and drying of wheat requires that the operator learn certain new operational and management skills. Past recommendations for wheat drying were primarily based on the assumptions of using unheated air and that initial moisture contents would be no higher than about 19%. Drying must be completed quickly with harvest moisture contents in the 20-25% range as recommended herein. Adequate air flow is required and heat is recommended, at least initially, to eliminate the high potential for spoilage at summertime temperatures. These and other management factors related to both harvesting and drying will be discussed in the sections that follow.

MANAGING HIGH-MOISTURE WHEAT HARVEST

One of the most difficult aspects of high-moisture wheat harvesting is knowing when to start harvest. The goal should be to harvest as early as good combine performance will permit, and still be assured of getting the wheat safely dried. This means shooting for a starting moisture of 24-26%, and then following the drying recommendations discussed later. If

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a hopper or two is harvested at 25-33% moisture, this will go to the bottom of the drying bin and be the first wheat dried. So some built-in margin of safety is provided. Just don't try to leave 33% wheat in a hopper or on a truck overnight, or you will shovel the spoiled mash into the trash!

A basic problem concerns moisture measurement. The accuracy of commonly available dielectric moisture meters diminishes as the grain moisture content goes up. Accuracy is usually adequate up to about 24% moisture. Above 24%, the readings may need to be cross-checked by other meters, or by oven drying of a few samples. 2

The moisture content of standing wheat may go up and down daily as much as 6-10 points, for example on days with heavy, early morning dew conditions followed by a hot breezy summer afternoon and subsequent high humidity nighttime conditions. During cloudy, rainy weather the wheat moisture may hover in the 18-24% range for several days. So, it's important to develop a reasonably accurate technique for knowing moisture content.

Combine performance will probably "tell" the operator if the wheat is too wet to harvest. Flow of material through the header will be a continual problem at grain moisture contents much above 25% or with wet, green stems. The material simply won't feed into and through the machine. Wait 2-4 hours if it's a good drying day, or wait until tomorrow if it's not.

In setting up the combine, start with the manufacturer's recommendations for "normal" wheat harvest. This includes settings for cylinder speed, cylinder-concave clearance, screen openings and fan blast. To fine-tune the combine for high-moisture wheat it may be necessary to adjust cylinder and fan speed, but other adjustments will probably not be required.

For good threshing, the cylinder speed may need to be increased by a few RPM. Check the threshing job periodically as conditions change, and back off on cylinder speed as permitted. Limited observation indicates that kernel damage--mashed or broken kernels--is <u>not</u> a serious problem even at kernel moistures up to 24-26%, but this may depend on combine make and wheat variety. In 1977 wheat was harvested at 33% with dry stems without any noticeable kernel damage. Indentations in individual kernels (but seed coat not broken) may be abundant with high-moisture harvest. These usually disappear as the wheat is dried.

Expect more chaff in the grain tank when harvesting high-moisture wheat with the "normal" fan setting. The wet chaff is heavier and simply won't blow out as easily. Fan speed can be increased to clean up the wheat in the grain tank, but then wheat may be blown out the back. Shoot for a compromise! Be willing to accept more chaff in the wheat than is desirable. If it's distributed well in the drying bin, little difference will be noted when the dry wheat is removed.

Shatter at the header is the major source of harvest loss when harvesting wheat at high as well as at normal moistures. Table 1 presents only 2-year data, but indicates the level of machine losses at several harvest moistures. To estimate field losses, figure each 12 to 20 kernels per square foot (depending on variety) represents one bu/a loss. Checking <u>in front</u> of the combine (in standing wheat) gives preharvest loss only; <u>under</u> the combine gives preharvest plus header loss; and <u>behind</u> the combine gives preharvest plus header plus rack and shoe loss (total loss).

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2 Use a 100-200 gram sample, spread on a cookie sheet, in a 260 - 270 F (130 C) oven. Recommended drying time is 19 hrs, but the error at 6 hrs is small. Moisture content (%, wet basis) is 100 x (initial wt - final wt) /initial wt.

One final note on harvest and handling: high moisture wheat doesn't flow as easily as dry wheat. After it's been jostled a few miles over a rough road, or left to sit for a while, it may not flow at all when the tailgate is raised. Some "manual help" may be needed when unloading trucks and wagons. Observe personal safety precautions! Be aware of the safety hazards that flowing grain presents--when it does begin to flow. Keep children away from harvesting, hauling and handling equipment.

Remember too, that spoilage can occur in a matter of a very few hours. Cooling and aeration must be begun very soon after harvest.

METHODS OF DRYING WHEAT

Both high speed and bin drying methods can be used for drying wheat. Past recommendations for unheated air drying were based on harvest moisture contents no higher than 19%. The reliability of unheated air drying is best at moisture contents at or below 19% (see Table 2 for air flow requirements). In general for heated air drying take care to hold input drying air temperatures below 140 F to avoid damage to milling quality of commercial wheat. For seed wheat, the kernel temperature limits should not exceed 110 F, with 100 F or lower even safer.

Heat damage in most grain drying is a time-temperature relationship. It is not just a question of how high the temperature, but also the exposure time. In general, heat-damage is much more likely to occur when initial moisture contents are high, because the heat must be applied longer at a given temperature. Thus, the higher the initial moisture content, the lower should be the air temperature, for either commercial or seed wheat, to avoid potential heat damage.

HIGH SPEED BATCH AND CONTINUOUS FLOW DRYING PROCESSES

High speed drying systems, designed primarily for corn drying, usually have excessive capacity for wheat drying. With the high air flow rates common to such dryers (frequently 50 to 100 cfm per bushel or more for corn) no heat may be needed. If heat is used, fire the burner only for short time intervals, or at a reduced heating rate for continuous burner operation. On many dryers the gas burner orifices can be changed to reduce the heat output of the burner.

Very little research has been conducted to determine the effect of high drying air temperatures on grain kernel temperatures as can be expected in crossflow, counterflow, rotary or concurrent flow dryers. Kreyger (1972) at the Institute for Storage and Processing of Agricultural Produce, Wageningen, The Netherlands, concluded from crossflow drying tests that in removing 4 points of moisture or less, the maximum wheat temperature to prevent deterioration of baking quality is 175 F (80 C), and in removing more than 4 points, the temperature should be limited to 140 F (60 C). Lindberg and Sorenson (1959) reported and recommended the temperature limits shown in Table 3. Their research was conducted in Sweden using a rotary dryer. Keep in mind that in crossflow and rotary dryers part of the wheat is at, or close to, the drying air temperature for the entire drying period. Also, that biological death and deterioration rates that influence germination and baking are based on the combination of both time and temperature.

Kreyger, J. 1972. Drying and storing grains, seeds and plants in temperate climates. Institute for Storage and Processing of Agricultural Produce: Wageningen, The Netherlands.
Lindberg, J.E. and I. Sorenson, 1959. Wheat drying. Kungl. Skogsoch Lantbruks - Akademiens Tidskr., Suppl. 1: Stockholm, Sweden

Wheat drying tests by Bakker-Arkema et al. (1977) in Michigan show the maximum wheat grain temperatures attained in concurrent flow dryers at various air temperatures. Data in Table 4 are extracted from Bakker's results. He states that wheat can be dried in concurrent flow dryers at temperatures as high as 525 F (121 C) as long as the wheat kernel temperatures remain below 145 F (63 C).

IN-BIN DRYING

Bin drying is easily adapted for wheat. Except for batch drying in shallow layers in the bin (batch-in-bin drying), these techniques generally rely on relatively low air flow rates (2-5 cfm/bu) and little or no supplementary heat (no more than 3-20 F temperature rise). Drying is slow! In-storage bin drying usually involves a more simple, less expensive equipment system than with high speed dryers, but is more vulnerable to mold due to the slower drying rate.

The drying rate of bin drying processes can be increased by several techniques. The use of batch-in-bin, grain stirring, recirculators and traveling loader-unloaders render many bin dryers capable of rapid drying. All of these techniques are adaptable to wheat, provided the fill depth is adjusted to compensate for the higher resistance to air flow of wheat as compared to corn.

MANAGING BIN DRYING BY HARVEST MOISTURE CONTENTS

If harvest moisture content is 24% or greater, heat is required until the top layer of wheat in a bin is dried to 19%. If the moisture content is 20% to 24% initially, the use of heat is advised until the top layer is below 20%. After drying to about 19% or if harvest is in the 16% to 19% range, natural unheated air can be satisfactorily used to dry the wheat to about 15% using 24 hr/day fan operation. Unheated air can also be used to dry a bin of 15% wheat to 13% by selecting low humidity days for finishing the drying. The final moisture level is determined by the equilibrium moisture content of the unheated air (see Table 5). This is discussed further under <u>Fan Operation</u>.

If heat is used to dry all the wheat in an unstirred bin to 13.5% there is a tendency to overdry the wheat in the bottom of the bin 2-4 percentage points. The overdried wheat can be rewet by operating the fan at night or during high humidity weather. However, this process is difficult to monitor and may result in wet spots and non-uniformity of moisture content.

A rule-of-thumb is to add heat until the drying front passes the top layer, and then finish the process with unheated air.

MOLD DEVELOPMENT

There are roughly 7 to 10 days available to reduce the moisture content of 24% wheat to less than 19% at summertime temperatures before mold development becomes critical. Mold is of greatest concern when grain moisture content is high, temperatures are warm, and the drying rate is slow. The rate of mold activity roughly doubles with each 10 C (18 F) rise in temperature. Thus, rate of mold activity is doubled when the grain temperature is increased from 60 to 78 F and doubled again if allowed to go from 78-96 F (or four times the 60 F rate).

Bakker-Arkema, F.W., A. Ahmadnia-Sokhansanj and R. Green. 1977. High temperature wheat drying. ASAE Paper No. 77-3527. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Therefore, try to keep the grain as cool as possible in low temperature drying. This means that in bin drying systems (low temperature, slow dryers), it is extremely important that the drying fan be run day and night to take advantage of cooler nighttime temperature and to reduce the time required for the drying front to reach the last grain to be dried. If the nighttime drop is 20 F (and this applies about half of each 24 hours), average temperature of the grain will be reduced 10 F. This should cut the rate of mold activity roughly one-fourth.

FAN OPERATION

Fans on unheated air wheat drying systems should run continuously day and night, rain or shine, until the grain is down to about 15% moisture. Until this 15% level is reached, more total drying is done by day-night operation than by day operation alone. The reason is that the grain dried in the lower layers during the day absorbs some moisture from the humid nighttime air. This has the effect of "drying the air out" and rendering it capable of doing drying in the upper layers. The result is more total drying for the 24-hour period, a faster-moving drying front, and a more uniform top-to-bottom moisture content.

Farmers frequently are too conservative when it comes to fan control on very low-heat or no-heat drying systems, worrying that they will undo what they have already accomplished in drying. The emphasis must be on keeping the fan running to keep the grain cool, until the moisture content is about 15%.

When wheat moisture content reaches about 15%, the gain in moisture during the night generally offsets the drying done during the day. Additional drying may then be accomplished by operating the fan only during the daytime when relative humidities are low. This should require no more than a week of daytime-only operation to dry the grain to 13.5% moisture.

Table 5 presents equilibrium moisture contents of wheat for selected air humidities. These data can be used as a partial guide for fan operation. For instance, 90% relative humidity air is capable of drying wheat only to 19.7% moisture (wb). With 60% RH air, however, wheat can theoretically be dried on down to 11.9% moisture.

INFLUENCE OF HEAT ON MOLD GROWTH

For in-storage and deep-bed drying processes, the proper use of heat needs to be approached with an understanding of what is involved. The indiscriminate use of heat can create more problems than it solves!

As the drying air temperature is successively increased in a deep bed of grain, the rate of mold activity, as noted earlier, will probably increase more rapidly than the rate of drying. This means that the time for the drying front to reach the upper surface before serious mold deterioration occurs will rapidly diminish. Either the drying rate must be increased or the drying depth decreased.

For a given fan size and grain depth, the only way to increase drying rate is to turn up the heat. But in deep beds of grain (4' to 16' deep) this will cause serious overdrying in the lower layers. The only practical solution then, if air temperatures are to be increased, is to reduce grain depth or stir. Either of these for a given installation, will cause total air flow and the drying rate to increase.

Fuel efficiency is usually good in any grain bed depth 2-3 feet or greater. Thus, these suggested changes in drying procedure will leave fuel efficiency relatively unchanged.

AIR FLOW, STATIC PRESSURE AND FAN HORSEPOWER

Specifications for an unheated air, in-storage wheat drying system are presented in Table 2. The table can be used either in selecting a fan for a new drying installation, or in determining how much small grain of a given moisture content and depth can be dried with existing corn drying equipment.

FLOORING AND DUCT SYSTEMS

In adapting existing overhead and ground level bins, full false floors are recommended. The channel lock perforated floors and corrugated perforated floors commonly used in round metal bins are available from most bin dealers in uncut lengths. The finished floor should have at least 7% opening.

Commercial duct systems are available for use in aeration systems in existing and new bins. Duct systems are not generally used in new bins where significant drying is to be done. Simple duct systems for existing small bins may be placed on the floor surface.

HEAT SOURCES, SOLAR, LP, ETC.

Wheat can be successfully dried using air heated from any one of a number of heat sources. Most commonly used are liquid petroleum, natural gas and electricity. Other potential heat sources are solar, coal, waste heat, crop residues, etc. No one source is necessarily better than another. Choice is a matter of availability, existing facilities and economics.

In general, wheat drying with solar heat or other sources is not recommended unless the facilities are already available and capital costs are already justified for some other drying and storage purpose. An example is for corn in the Midwest. Of course, this is not necessarily so for special cases such as high quality seed production, or at locations where wet weather persists throughout the time of harvest.

Research at Purdue, sponsored by ERDA and conducted by ARS, USDA, has shown that wheat can be safely and satisfactorily dried in a bin with solar heated air in from 12 to 14 days in late June and early July. This assumes a maximum temperature of input air of about 120 F, between 2 and 3 cfm/bu air flow, and initial moisture content 25% or less. Stirring the grain helps shorten the time required to effectively reduce the moisture content of the critical top layer, or any other concentrated part of the grain mass, to below 20% and thereby slow mold growth to a point that drying can be accomplished before spoilage occurs. Remember that there are only 7 to 10 days to get aerated wheat below 19% in mid-summer in the Midwest. Equally important is the fact that there are only a very few hours to get air on the wetter-than-20% mass of wheat before it begins to spoil.

The time required to in-bin dry wheat varies according to management practices. First, you should not dry wheat with unheated air at moisture contents above 19-20%. Otherwise in-bin drying from 19-20% on down to about 13% can be accomplished with 2-3 cfm/bu air flow. This will take 2 to 4 weeks of continuous aeration, according to weather conditions. In 1977 it took 30 hours to in-bin dry 25% wheat down to 19%, using 2.5 cfm/bu, with stirring, using LP heated air to provide a 35 to 40 F temperature rise. Drying was then finished to 13.5% with unheated air. Estimated time to finish with continued use of LP heat would have been about 24 more hours in addition to the 30. If this level of heat had been used without stirring, care would have to have been taken to avoid over-drying the grain in the bottom of the bin.

To summarize three or four important points:

1. Wheat can be in-bin dried with solar heated air although a solar drying system cannot be economically justified to dry only wheat,
2. High temperature in-bin drying, 40 F rise, is quick and satisfactory, especially if the grain is stirred,
3. Unheated air drying cannot be depended on with initial moisture contents above 19-20%, and
4. Most important, don't overfill your bin that was designed for corn drying and storage. The resistance to air flow through wheat is much greater than through corn. For example, about 6.5 to 7 ft is as deep as wheat should be dried in a bin designed for corn. If you put one more load in to finish a field you simply are taking too great a chance on spoilage!

ECONOMICS OF DRYING WHEAT FOR DOUBLE-CROP SOYBEANS [3]

Once a decision to try to double crop wheat and soybeans has been made, drying should be given serious consideration as this can add about $15-$20 per acre to income potential from double cropping. Early harvest of the wheat crop likely means about a 2% reduction in field losses. But more importantly, yield potential of the soybean crop increases by about 3/4 bushel per acre per day for each day planting is advanced during late June and early July.

The high moisture wheat harvest and drying decision can be made separately from the decision to double crop. Table 6 contains a partial budget detailing the added costs and returns for early high-moisture wheat harvest and drying, assuming that double crop soybeans will be planted. The table is based on an average 21% harvest moisture for wheat and assumes that planting date can be moved up 6 days as a result of this practice. This 6-day advantage in planting date increases the expected soybean yield by about 4.5 bushels per acre. With a soybean price of $5.00 per bushel, this means $22.50 per acre added soybean return--substantially higher than the added costs, even when custom drying charges for wheat are figured at 12 cents per bushel. On-farm drying in an existing facility may further increase the $17.10 per acre advantage calculated. The economic payoff is so great that drying should be considered as a standard practice in double cropping programs if drying facilities are available.

MANAGING GRAIN IN STORAGE

A small bin of top quality dry wheat can easily be worth $5,000. So it's worth looking after regularly! Keep reminding yourself that the grain is a valuable living product, being maintained in a God given, uncontrolled environment.

Form a regular habit of checking on the grain, daily while drying and weekly thereafter. This is especially important when the temperatures outside the bin are changing relative to that of the grain. The best advise is to <u>smell</u>, <u>poke</u>, <u>feel</u>, <u>and</u> <u>look</u>, <u>regularly</u>. Wheat dried to 13.5% with fines either cleaned or evenly distributed, and with a well-designed aeration system, managed correctly, should store satisfactorily on a year around basis.

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Table 1. Field losses for wheat harvested at different moisture contents.

Moisture content (%)	Pre-harvest losses (bu/a)	Harvest losses* (bu/a) Header	Rack & Shoe	Total
1976 (Stalks green)				
23	0.3	2.0	0.2	2.2
18	0.2	2.6	0.2	2.8
13	0.3	3.7	0.2	3.9
1977 (Stalks dry)				
28	0.1	---	---	1.6
25	0.1	---	---	0.8
20	0.1	---	---	1.7

*Data were taken from several fields. Wheat was harvested with a John Deere 660 combine, 925 RPM cylinder speed, 800 RPM fan speed. Yields were approximately 50 bu/a.

Table 2. Specifications and equipment performances for drying wheat with unheated air.

Initial moisture content (%)	Airflow required (cfm/bu)	Inches of water static pressure required to force air through a wheat depth of: 0.5'	1'	2'	4'	6'	8'	10'
<16	1	---	---	---	0.5	0.9	1.3	2.0
16-18	2	---	---	---	0.8	1.6	2.5	4.3
20-24*	4	---	---	---	1.5	3.3	---	---
>24**	5	---	---	---	1.9	4.3	---	---
	20	0.3	0.6	2.1	---	---	---	---
	30	0.4	0.9	3.5	---	---	---	---
	40	0.5	1.2	---	---	---	---	---
	50	0.6	1.6	---	---	---	---	---
		Bushels of wheat that can be dried per fan hp at various depths:						
<16	1	---	---	---	---	---	2300	1500
16-18	2	---	---	---	1880	940	600	350
18-20	3	---	---	---	830	440	230	---
20-24	4	---	---	---	---	---	---	---

* Heat is advised until the top surface or stirred mass reaches 19%.
**Heat is required until the top surface or stirred mass reaches 19%.

Table 3. Maximum allowable kernel temperatures of wheat used for seed and baking in a rotary dryer as a function of moisture content. Lindberg and Sorenson.

Moisture content (% wb)	Seed (C/F)	Baking (C/F)
27	50/120	50/120
25	51/124	52/126
23	53/127	55/131
21	55/131	57/135
19	58/136	60/140
17	60/140	64/146
15	63/145	67/153

Table 4. Temperatures and some tested qualities of soft wheat dried in a one-stage concurrent flow dryer, 14% MC basis, Bakker.*

Temperature (F) Drying air	Temperature (F) Wheat kernel	Moisture content (% wb)	Germination (%)	Test wt (lb/bu)	Cookie diameter (cm)
Control		14.0	93	60	18.2
250	98	16.4	71	59	18.2
300	104	15.9	71	59	17.4
350	112	14.3	--	--	--
400	115	14.0	51	58	17.4
450	---	12.8	28	56	17.1

* Grain flow rate 4.4 ft/hr, initial moisture content 18% wb, initial wheat temperature 85 F, air flow 65 cfm/sq ft, bed depth 2.0 ft.

Table 5. Equilibrium moisture contents for wheat at various humidities at room temperature.

	Equilibrium moisture contents at various relative humidities						
Wheat type	15%	30%	45%	60%	75%	90%	100%
Soft red winter	6.3	8.6	10.6	11.9	14.6	19.7	25.6
White	6.7	8.6	9.9	11.8	15.0	19.7	26.3

Table 6. Estimated profit from wheat drying and double cropping, based on 60 bu/a wheat yield harvested at 21% MC.

Added costs: Item	$/a	Added returns: Item	$/a
Wheat drying* (60 bu @ $.12)	$7.20	Reduced wheat losses** (1.2 bu @ $2.50)	$ 3.00
Extra hauling, handling shrinkage (60 bu @ $.02)	1.20	Increased soybean yield*** (4.5 bu @ $5.00)	22.50
TOTAL	$8.40		$25.50
		Net advantage: $17.10	

*Based on custom drying charges of $.12/bu to dry wheat from 21 to 13%. Farms with existing drying facilities would have out-of-pocket costs of about $.05/bu.
**Based on a 2% reduction in field losses. There may also be an added return from improved grain quality.
***Assume planting soybeans 6 days earlier with a yield increase of 3/4 bu/a/day. The break-even level for no-till double cropping for 1978 is expected to be about 12 bu/a if the price of soybeans is $5.00/bu.

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SOLAR GRAIN DRYING UNDER HOT AND HUMID CONDITIONS

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INTRODUCTION

Each year, the U.S. produces approximately 200 million tons of feed grains, 70 million tons of food grains and over 1.5 billion bushels of soybeans (4). Practically, all of these grains have to be dried for safe storage. The amount of energy used in grain drying represents a very large portion of the energy used in agriculture. It has been estimated (4) that the energy requirements for drying corn are 56 x 10^{12} Btu (59.1 x 10^{12} KJ), and for rice, 3 x 10^{12} Btu (3.2 x 10^{12} KJ). The fuel equivalent is about 640 million gallons (2.4 x 10^{9} liters) of LP gas.

There are several reasons why there is a need to harvest the grains early when their moisture contents are still high instead of letting them dry in the field. While in the field, the grains are subjected to stresses due to the drying and rewetting by dew and rain; they can also be contaminated by molds. At lower moisture contents, harvest losses are higher due to grain shattering. Finally, by harvesting the corn crop early, a second crop is possible on the same field.

Liquified petroleum gas and natural gas are the two main fuels used for grain drying. Since the energy crisis of 1973, solar energy has received renewed interest as an energy source for grain drying. This particular use of solar energy, a renewable energy source, has great potential since grain drying requires low temperatures and can tolerate diurnal variation that is characteristic of solar energy. Also, space for solar collectors is not usually a problem on the farm.

Several investigations on solar grain drying, mostly in the Midwest, have been conducted (2,8,9,10,12,13). The investigations were concentrated on what is usually referred to as low-temperature drying involving a temperature rise of a few degrees across the collector and drying takes place over an extended period of several weeks or months while the grain is in the bins.

In the South, the humidity and ambient temperature are higher than those in other parts of the country. These conditions make the grains very susceptible to spoilage if steps are not taken to reduce the grain moisture quickly.

Also, due to the special climatic conditions of the South, aflatoxin contamination of feed grain is of grave concern. Aflatoxin is a toxic mycotoxin produced by the Aspergilus flavus fungus. The toxicity of aflatoxin is well documented in the literature. It has been shown to be the cause of stunted growth, reduced milk production, liver injury, abortion of fetuses, birth of weak animals and even deaths to the animals at higher doses (1,5,6,11).

Under conditions of high susceptibility to aflatoxin contamination in the Southeast, special considerations have to be given to grain drying. If the sun is used as an energy source, the temperature rise across the collector and the rate of air flow through the grain most likely have to be much higher than the values normally used with solar dryers in the Midwest.

COLLECTOR DESIGN AND EVALUATION

One of the objectives of this work is to develop a low-cost solar air heater capable of moderate air temperature rises that can be used for crop drying and other applications requiring heated air. The collector under investigation is basically a plastic flat plate collector, with a black plastic screen suspended between the clear plastic glazing material and the black plastic absorber. Behind the black plastic, there is a layer of insulation boards to reduce heat losses. The plastic screen and the black plastic serve as the absorbing, heat transfer surface. The addition of the plastic screen increases the heat transfer area and the convective heat transfer coefficient between the absorber and the air. Since the heat transfer area is increased, the temperature of the absorber is reduced and heat losses to the surroundings are consequently less. Also, by operating at lower temperature, the useful life of the plastic absorber is extended. This type of plastic collector should be more efficient than the conventional plastic air heaters, especially when relatively high temperature rises are needed.

The experimental solar collector was 12 ft by 96 ft (Figure 1). It was constructed primarily from plastic materials and wood. The collector floor was made of urethane insulation boards, 1.25 in thick, with aluminum foil on both sides. The insulation boards were supported by 2 x 4's spaced 4 ft. apart, and laid on the ground. The collector was covered with a clear polyethylene and the floor was covered with a black polyethylene sheet. Between the black plastic and the clear plastic, there was a layer of black polypropylene screen (greenhouse shade cloth) with 45 percent open area. The sides of the collector consisted of 1 in x 8 in boards with poly-lock strips for mounting the clear plastic. At each end of the collector, there was a metal plenum to guide the air flow.

The range of air flow rates tested was from 1 cfm/ft^2 to 3.4 cfm/ft^2 of collector surface. During all tests, the collector was flat on the ground, with an East-West orientation.

Figure 2 shows that the efficiency definitely varies with air flow rates. As the air flow rate is increased, first, the operating temperature of the collector is decreased and heat losses are thus reduced; secondly, the convective heat transfer coefficient between the air and the plastic screen is increased, making the heat transfer more efficient. Because the back of the collector is insulated, most of the heat losses are radiative losses from the absorber and some convective losses through the clear plastic. Since radiative losses are related to the 4th power of the absolute temperature of the absorber, the reduction of the absorber temperature is very significant.

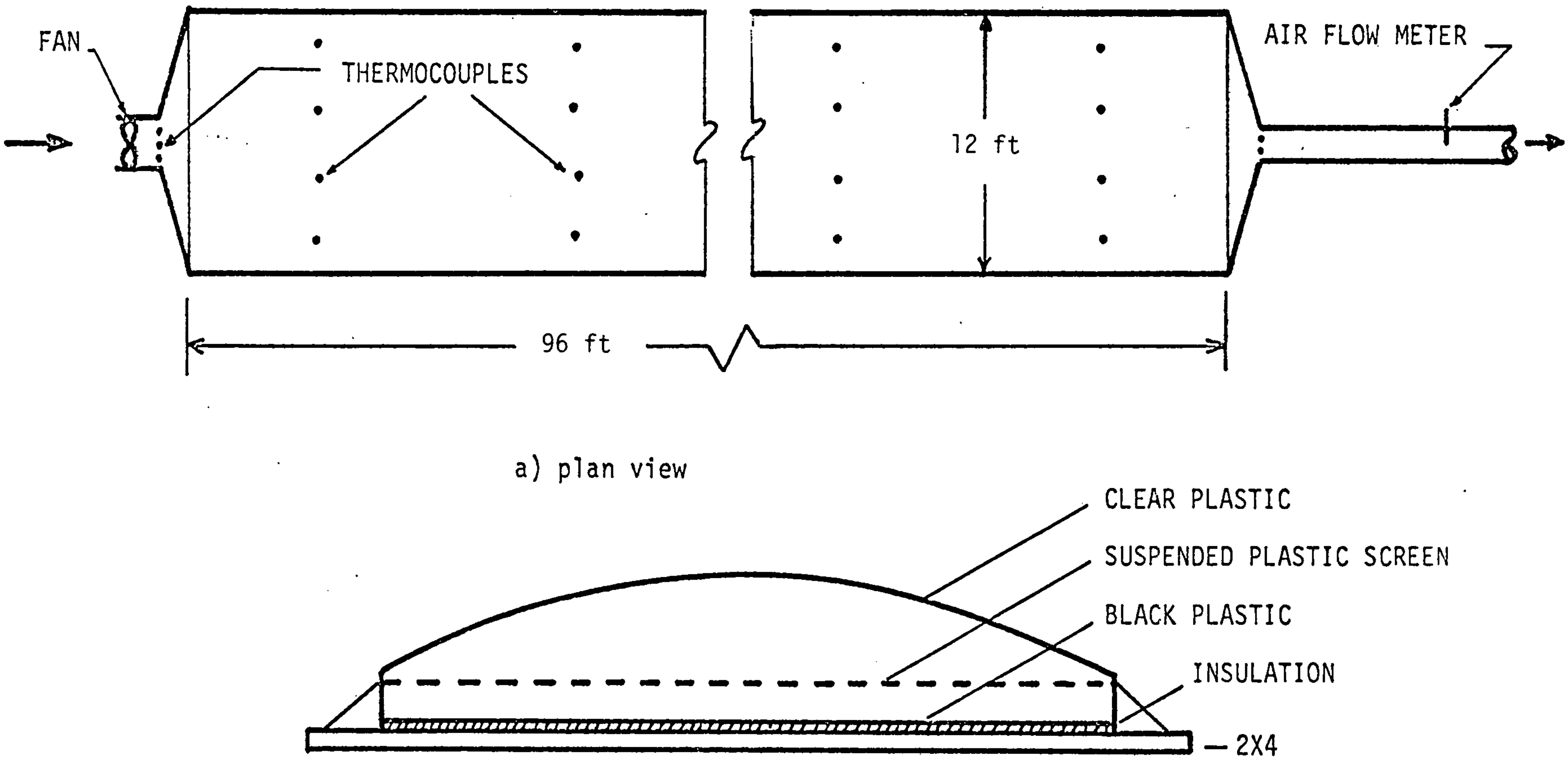
Full details on the performance of this collector has been presented in reference (3).

Economics

The cost of the collector, excluding labor, instrumentation and fans was \$1.00/ft^2. The insulation boards accounted for 32% of the total material cost and the two metal plenums at both ends of the collector accounted for another 30%. The plenums were custom-made and were rather expensive compared to the rest of the collector. The plastic screen cost only 8.7¢/ft^2 or about 9% of the total cost of materials.

If insulation were not used and less expensive plenums were used, it would be possible to bring the cost down to less than 50¢/ft^2. For collectors lying flat on the ground (most practical orientation of collector for grain drying in the south) the removal of insulation is expected to have little overall effect on the collector performance, since the ground provides some insulation and thermal storage. The next phase of this project will investigate such a collector, with much simpler plenums and no insulation.

For the collector under investigation, assuming a radiation rate of 1300 Btu/ft^2-day dur-the Fall when grain crops need to be dried in Florida, one can expect an average daytime temperature rise of 18°F at an air flow rate of 3 cfm/ft^2 of collector area or a heat gain of 455 Btu/ft^2-day. On the basis of 60¢/gallon of propane gas, this represents a fuel saving of 0.38¢/ft^2 day. During the Summer months, the heat gain is naturally higher.



a) plan view

b) cross-section

FIG. 1 Schematic diagrams of the plastic air heater.

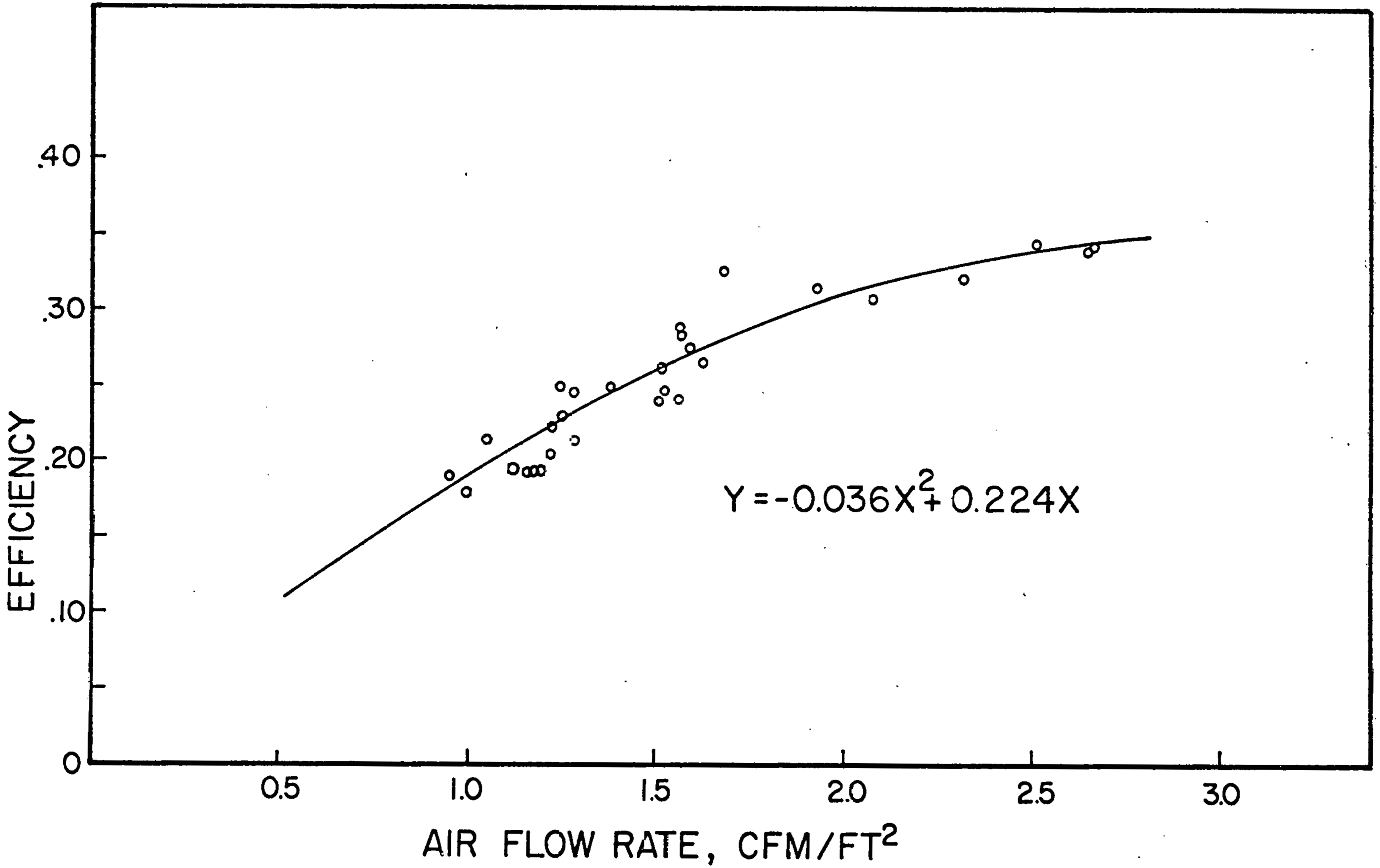


Figure 2. Collector efficiency vs air flow rate

GRAIN DRYING TESTS

1. Experimental Facilities

The 12 ft x 96 ft suspended screen collector was connected to two 100-bushel bins by two 12" ducts. The grain bins were corrugated sheet metal bins, 6 ft in diameter and 5 ft deep along their cylindical section, with perforated metal floors. A small sliding gate was installed on the side of each bin just above the perforated floor to unload the bins. A thermopile was placed in the plenum below the floor of each bin to measure the temperature of the air before entering the grain. In each bin, thermocouples spaced 6 inches apart were placed vertically in the grain bed to measure the vertical temperature profile inside the bins.

The bins are referred to either as the West bin or the East bin in this report. A weather shelter housed probes for measuring ambient, dry bulb and dew point temperature. All input data were recorded on magnetic and paper tapes by a data acquisition system that scanned every 5 minutes.

2. Experimental Procedure

Known weights of grain were brought in by truck and loaded in the bins with an auger conveyor.

Grain moisture samples were taken twice a day with a sampling tube that had sample compartments 6" apart. Samples were taken in the morning at the start of the day run and in the late afternoon at the end of the day run. Moisture determinations were made by the oven method.

Samples for aflatoxin determination were taken when the grain was first brought in from the field, at the start of the drying test (the following morning), and at the end of the drying tests. Samples were taken at two levels, one just above the bin floor and the other a few inches below the top level of grain in the bin.

Air flow rates through the collector and through the grain bins were measured at least twice a day and all the temperatures and weather data, including insolation, were recorded every 5 minutes.

Heated air from the collector was let into the grain bins after 9 a.m. to give the collector an opportunity to evaporate most of the moisture condensed on the underside of the clear plastic during the previous night. The top of the transition box was opened at night to direct air away from the grain bins. The collector was kept inflated continuously to avoid damage due to trapped rain water.

At night, the grain bins were subjected to one of the following three modes of operation:

a) no air flow through the grain
b) continuous air flow through the grain
c) the bin blower was controlled by a humidistat

If one of the blowers connected to the bins was controlled by the humidistat in the evening, an event recorder was also used to indicate the time when the blower was shut off.

3. Results and Discussion

a) Drying tests.

All the tests were conducted with solar energy as the only source of heat; there was no auxiliary heat source.

Originally, it was planned to test two drying regimes, a fast drying regime involving high temperature rises across the collector and high air flow rates through the grain and a slow drying regime with low temperatures and low air flow and requiring about two weeks or more to complete the drying. However, due to the high ambient temperature and humidity, mold growth during drying was a problem and practically all of the tests were completed in a few days. The longest test was 8 days to bring the grain to around 13% (db).

Table 1 shows a summary of the 1977 drying tests.

The data from Table 1 indicate that solar energy can remove an appreciable amount of moisture from the grain and the drying time can be short. However, because of the differences between tests in terms of grain weights, moisture removed and the relative percentage of the air from the collector that was actually circulated in the bins (in many cases, part of the air from the collector was dumped out) it is rather difficult to evaluate drying performances from the data presented in Table 1. The data were therefore normalized on the basis of one ft^2 of collector area and an average moisture content reduction of one percent per day. In other words, for each square foot of collector area, how many bushels can be expected to be dried at an average rate of one percent moisture loss per day, under the same conditions of grain depth, initial moisture content, air flow rate, collector efficiency, etc. as in the tests. Table 2 presents the results of this normalization process for the corn tests of 1977 and the corn and soybean tests of 1976.

Table 2 shows that under the conditions tested, a maximum of 1.82 bushels can be reduced one percentage point of moisture per day for each ft^2 of the collector, if the grain depth is 4.9 ft, the air flow rate is 4.4 cfm/bu and a temperature rise across the collector of 23.3°F. The minimum is 0.32 bu with a grain depth of 2.5', an air flow rate of 8.3 cfm/bu and a temperature rise across the collector of 40.1 degrees.

b) Grain depth.

As expected, drying efficiency increases with increased bed depth. Table 3 shows the amounts of water removed from the bottom half of the grain bed and from the entire bed. In order to have a fair comparison, the data were cut off when the average moisture content of the bottom half of the grain bed was close to 13% (db).

Table 3

Test No. 1	Bottom Half		Entire Bed	
	East Bin	West Bin	East Bin	West Bin
Grain depth, ft	2.45	2.45	4.9	4.9
Moisture removed, lbs	615.7	617.6	831.1	788.8
Final MC % (db)	12.52	11.69	20.14	20.49
Drying time	5 days	5 days	5 days	5 days

It can be seen that more moisture is removed from a deep layer than from a thinner layer.

Also, while it took 5 days and nights to bring the grain to 12.52 and 11.69% moisture contents (db) for the bottom half of the East and West bins respectively, it took only an extra 3 days to bring the entire two bins to 10.43% (db) and 11.34% (db) respectively.

However, while a deeper layer is more efficient from an overall water removal standpoint, it also produces a very large moisture content gradient in the grain bed (Fig. 3), with the bottom layer overdried and the top layer remaining at high moisture content for a long time. This could induce mold growth and grain spoilage in the upper layer.

c) Night mode.

Circulation of air through the grain at night may add moisture to the grain but it will reduce the moisture gradient across the grain bed as illustrated by Figure 3. Also, the night air cools the grain. These two factors may have a possible effect on the control of aflatoxin production, especially in the top layer of the grain bed.

Several tests were conducted with one of the bins receiving ambient air continuously at night and the other bin on a humidistat setting. The humidistat was set to shut off the blower at relative humidity beyond 80%, but the actual shut off level was 87%. Table 4 on the next page shows a summary of the results.

As seen in Table 4, less water was removed when air was blown continuously through the grain at night as compared to the case where the air was stopped when the relative humidity reached 87% during the night. The 1976 tests gave the same results. Table 4 also shows that the relative humidities at night were very high, except during Test No. 4 when it averaged only 63%.

TABLE 1. SUMMARY OF THE 1977 TESTS

	Test No. 1 Corn		Test No. 2 Corn		Test No. 3 Corn		Test No. 4 Corn	
Date Started	7/22/77		8/4/77		8/10/77		9/15/77	
	East Bin	West Bin	East Bin	West Bin	East Bin	West Bin	East Bin	West Bin
Batch Size, bu	111.2	111.2	56.5	56.5	56.5	56.5	79.2	79.2
Grain Depth, ft	4.9	4.9	2.5	2.5	2.5	2.5	3.5	3.5
Air Flow Rate, cfm/bu	4.4	4.4	12.7	13.1	14.2	14.1	8.3	8.4
Night Mode	Humidistat	Continuous Air	Humidistat	Continuous Air	No Air Flow	No Air Flow	Humidistat	Continuous Air
Initial MC (% db)	36.19	35.67	27.94	27.84	24.25	25.11	16.90	16.75
Final MC (% db)	10.43	11.34	12.55	12.81	14.48	14.47	11.85	12.51
Avg. Daily Insolation (Btu/ft^2)	1647.3		1724.2		1592.7		1204.5	
Avg. Temp. Rise, °F	23.3		24.5		34.8		40.1	
Avg. Daytime RH, %	63.3		60.1		69.0		62.3	
Avg. Nighttime RH, %	93.5		96.1		99.8		63.1	
Drying Time, days	8		2		2		2	

	Test No. 5 Soybeans		Test No. 6 Soybeans		Test No. 7 Soybeans	
Date Started	11/2/77		11/15/77		12/9/77	
	East Bin	West Bin	East Bin	West Bin	East Bin	West Bin
Batch Size, bu	41.2	41.2	98.3	98.3	91.9	91.9
Grain Depth, ft	2.0	2.0	5.2	5.2	4.6	4.6
Air Flow Rate, cfm/bu	9.3	9.3	7.5	7.5	4.6	4.6
Night Mode	Humidistat	Continuous Air	Humidistat	Continuous Air	Humidistat	Continuous Air
Initial MC (% db)	18.55	18.58	22.32	18.03	18.46	19.33
Final MC (% db)	16.65	16.62	16.25	13.49	15.57	15.23
Drying Time, days	5	5	4	4	6	6

TABLE 2

Test No.	Type of Grain	Grain Depth ft.	Flow Rate cfm/bu.	Initial MC % (db)	Avg. Daily Radiation Btu/ft^2	Temp. Rise °F	Number of bushels that can be dried at an average rate of 1% MC (db) per day by 1 ft^2 of collector			
							Bu.	Night Mode	Bu.	Night Mode
1 (1976)	Corn	4.5	6.3	15.3	1529.6	27.7	0.55	S*	0.54	S*
2 (1976)	Corn	4.6	6.2	15.3	945.5	23.2	0.53	S	0.47	C
3 (1976)	Soybeans	4.2	11.6	20.0	1060.0	20.6	1.27	S	1.04	C
4 (1976)	Soybeans	3.8	13.6	21.5	1085.9	21.1	1.21	S	1.14	H
5 (1976)	Soybeans	5.0	6.4	17.9	845.4	14.9	1.50	S	1.44	C
1 (1977)	Corn	4.9	4.4	35.9	1647.3	23.3	1.75	C	1.82	H
2 (1977)	Corn	2.5	12.9	27.9	1724.2	24.5	1.54	C	1.52	H
3 (1977)	Corn	2.5	14.1	24.7	1592.7	34.8	0.67	S	0.61	S
4 (1977)	Corn	3.5	8.3	16.8	1204.5	40.1	0.39	C	0.32	H

*S: Air flow stopped at night
C: Continuous air flow at night
H: Blower on humidistat

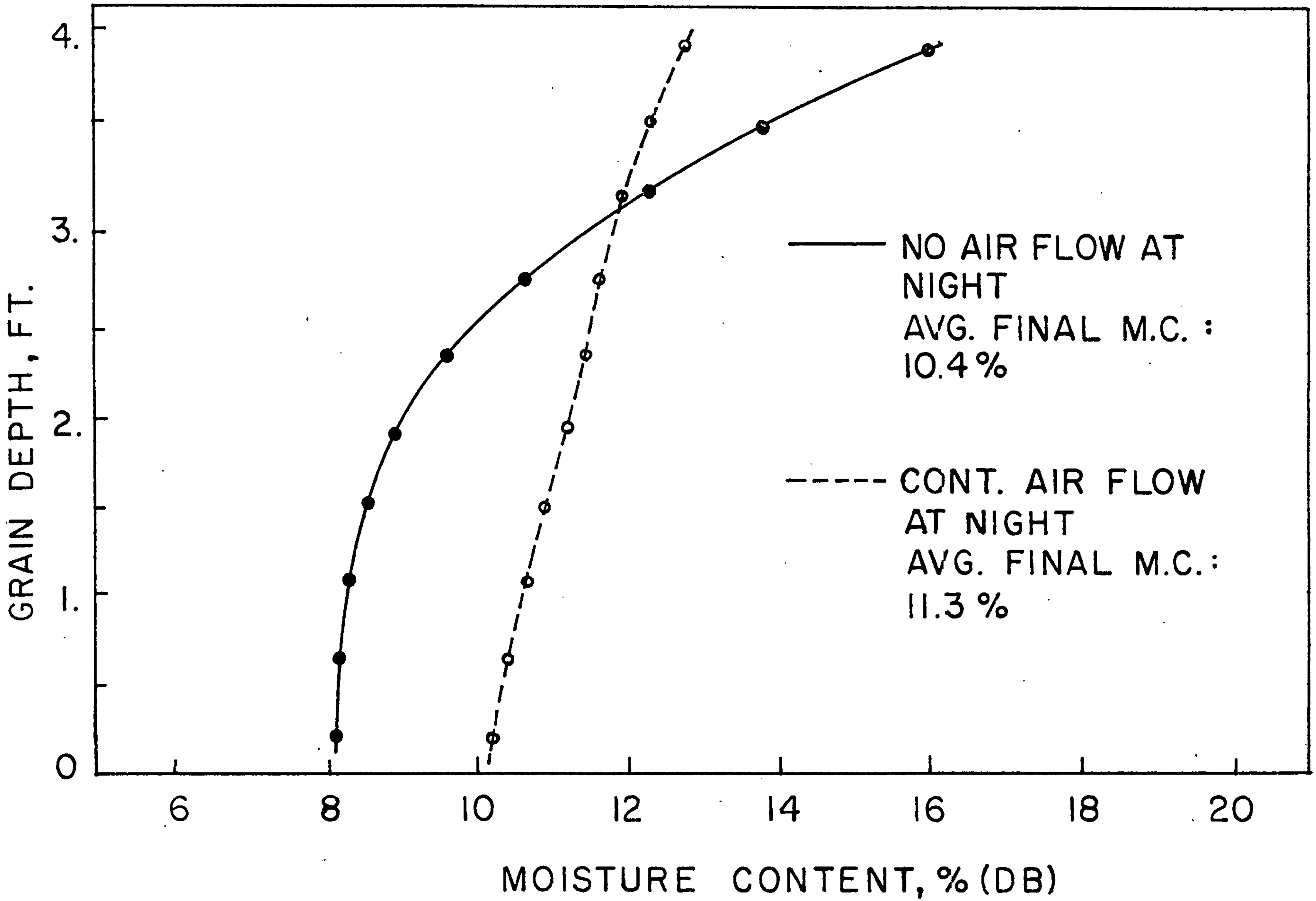


Figure 3. Typical moisture profiles at the end of a test.

Table 4

	Total Water Removed, lbs		
	Continuous air-flow at night	Humidistat control	Average night relative hum.
Test No. 1	1264.2	1385.4	93.5
Test No. 2	422.1	431.8	99.8
Test No. 4	178.1	216.8	63.1

Also, the data showed that air circulation at night does have some advantages in terms of drying efficiency. Early in the drying cycle, when the grain moisture was still high, the data indicate that even at high relative humidity, the night air still removes moisture from the grain and it adds moisture to grain only towards the end of the drying cycle, when the average moisture content of the grain is low.

d) Aflatoxin contamination.

All of the corn used in the drying tests was contaminated with aflatoxin due to the difficulty in getting aflatoxin-free corn.

The aflatoxin levels in the different tests in 1977 are presented in Tables 5 and 6.

TABLE 5. SUMMARY OF AFLATOXIN LEVELS IN CORN

Test No. 1. Initial MC 35.9%	Night Mode			
	Continuous Air		Humidistat	
	Bottom layer	Top layer	Bottom layer	Top layer
Start of drying	no data	no data	no data	no data
4 days after, ppb	115	5591	no data	10094
10 days after start, ppb	133	7554	no data	11994

Test No. 2. Initial MC 27.9% 2.5 ft deep; 12.9 cfm/bu	Night Mode			
	Continuous Air		Humidistat	
Field sample: 46 ppb	Bottom layer	Top layer	Bottom layer	Top layer
Start of drying, ppb (one day after harvest)	62	205	102	311
4 days after start, ppb	61	569	36	67

Test No. 3. Initial MC 24.7% 2.5 ft deep; 14.2 cfm/bu	Night Mode			
	No Air Flow		No Air Flow	
Field sample: 166 ppb	Bottom layer	Top layer	Bottom layer	Top layer
Start drying, ppb (one day after harvest)	676	400	118	460
2 days after start, ppb	139	140	81	220

Test No. 4. Initial MC 16.8% 3.5 ft deep; 8.3 cfm/bu	Night Mode			
	Continuous Air		Humidistat	
Field Sample: 506 ppb	Bottom layer	Top layer	Bottom layer	Top layer
Start of drying, ppb (one day after harvest)	742	263	877	642
4 days after, start ppb	406	989	1048	1089

TABLE 6. SUMMARY OF AFLATOXIN LEVELS IN SOYBEANS

Test No. 5. Initial MC 18.6%	Night Mode			
	Continuous Air		Humidistat	
Field sample: negligible	Bottom layer	Top layer	Bottom layer	Top layer
Start of drying, ppb (one day after harvest)	neg.*	neg.	neg.	neg.
5 days after start, ppb	neg.	neg.	neg.	neg.

Test No. 6. Initial MC 20.2%	Night Mode			
	Continuous Air		Humidistat	
Field sample: negligible	Bottom layer	Top layer	Bottom layer	Top layer
Start of drying, ppb (one day after harvest)	neg.	neg.	neg.	neg.
4 days after start, ppb	neg.	neg.	neg.	neg.

Test No. 7. Initial MC 18.9%	Night Mode			
	Continuous Air		Humidistat	
Field sample: negligible	Bottom layer	Top layer	Bottom layer	Top layer
Start of drying, ppb (one day after start)	neg.	neg.	neg.	neg.
6 days after start, ppb	neg.	neg.	neg.	17

*negligible

Several general remarks can be made from these results. When the grain is already contaminated, drying has to be completed within a very short time or the aflatoxin level will increase rapidly. The top layer of the grain bed usually has a higher level of aflatoxin due to the slower drying rate in the top layer. Continuous air flow through the grain at night appears to decrease the rate of aflatoxin accumulation. This is probably due to the fact that night air cools the grain and also reduces the moisture gradient across the grain bed.

Soybeans which were free from aflatoxin coming in from the field showed a negligible amount of aflatoxin accumulation during solar drying. It should be noted that soybeans were harvested in November and December when the ambient temperatures were mild and the moisture contents at harvest were fairly low (18-20% dry basis).

These results are very preliminary; further tests are needed to be conclusive. Sampling techniques for aflatoxin determination need to be refined also. Since only minute amounts of aflatoxin are present in the grain, sampling errors could be significant unless very large samples are taken.

SUMMARY AND CONCLUSION

The plastic collector with a suspended screen performed well and compared very favorably with other types of plastic collectors. It was capable of raising the air temperature by an average of over 40°F during the day. Its cost of $1.00/ft^2 (material cost) can be further reduced.

One thousand square feet of this collector can be expected to reduce up to 1800 bushels of corn by an average of 1% moisture content (db) per day. However, at this rate, aflatoxin contamination may be a significant problem.

Hot and humid ambient conditions add new constraints on solar grain drying. The grain has to be dried immediately after harvest, and the drying time has to be reduced to a minimum, a few days or even less. This means that a high temperature rise across the collector, a high air flow rate through the grain, and a relatively low initial grain moisture content are required.

Solar collectors are more efficient when the temperature rise across the collector is low. But with low temperature rises, the drying time is increased and so is the susceptibility to aflatoxin contamination by the grain. Drying is more efficient when the grain bed is deep but aflatoxin production during drying is also high because of the high moisture content of the top layer of the grain mass. Circulating cool night air through the grain mass adds moisture to the grain but seems to reduce aflatoxin production, probably because of the lowering of the grain temperature and the reduction of the moisture gradient in the grain bed. When the grain is already contaminated with aflatoxin, the overnight wait between the loading of the bin and the start of solar drying the following morning does add an appreciable amount of aflatoxin to the grain.

Tests with soybeans indicate that when the grain is free of aflatoxin, aflatoxin production during drying is minimal if the drying time is less than 6 days. It should be noted, however, that the soybean tests were done in November and December when ambient temperatures are relatively mild.

More information is needed on the rate of aflatoxin production as a function of ambient conditions and grain moisture in order to design a solar drying system that will perform well. Without this information, the designer does not know the maximum allowable drying time, and consequently cannot determine whether or not solar drying is feasbile or economical.

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SOLAR COLLECTORS FOR LOW TEMPERATURE GRAIN DRYING

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INTRODUCTION

Solar energy collectors of various types were investigated for use in drying grain. The performance of 12 different solar collectors is reported for this conference.

SOLAR COLLECTOR TESTS

Pilot scale collectors suitable for low temperature grain drying were designed and constructed. The collectors, except for one, were of the flat-plate type with air as the heat exchange medium. The collectors were 30 feet in length and 3 feet in width or diameter for an effective absorber area of 90 square feet. During the tests, the collectors were in fixed position, south facing, and elevated to the optimum angle, except the semi-circular shaped collector which had a horizontal absorber surface. One of the collectors was of the concentrating type with air as the heat exchange medium.

Tests were conducted during the fall and spring grain drying seasons to measure the amount of energy that could be collected by the different types of collectors. For the comparative tests, the solar collectors were operated simultaneously and airflow rates were identical. The temperature rise of a known quantity of air was measured to determine the energy collected and the efficiency of the collectors. Incoming solar insolation was measured by pyranometer. Wind speed and direction and other weather factors were recorded. A data acquisition system, including microprocessor control, recorded data at six-minute intervals.

SOLAR COLLECTORS

The solar collector configurations and types are shown in Figure 1. The materials used for cover plates, absorber surfaces, and back and side plates are listed.

Two of the solar collectors were of the air-supported type using polyethylene film. For test purposes, the air-supported type collectors were modified so the polyethylene film was supported by welded wire mesh. Air was pulled through these collectors rather than using air under pressure so that accurate measurement of the air temperature rise could be obtained. One of the polyethylene film collectors was semi-circular in shape with clear polyethylene as the cover plate and a horizontal absorber of black polyethylene on the ground. The other collector was a circular tube of clear polyethylene with black polyethylene across the diameter of the tube as the absorber surface.

Two other solar collectors were of rigid frame construction and triangular in shape. One was a bare plate collector utilizing corrugated metal roofing as the absorber surface and simulating the use of the roof of a building as a solar collector. The other triangular shaped collector used plywood painted black as the absorber surface. The cover plate was corrugated fiberglass similar to that used in greenhouses.

One collector incorporated chipboard for both the absorber and the back plate with the suspended absorber plate painted black. The cover plate was corrugated fiberglass supported in an arch shape using hardboard ribs. Another collector was of the concentrating type. The parabolic reflector surface was formed with hardboard and covered with aluminum foil. The absorber surface was a 13 inch diameter pipe painted black.

The remaining six solar collectors were of the flat-plate type and rectangular in shape. Two of the collectors incorporated a single air channel under the absorber plate. The other four collectors had suspended absorber plates with air moving above and below the absorber plate.

One of the single air channel collectors was a bare plate collector using corrugated metal roofing as the absorber surface. The air channel was sized to provide testing with a wide range of airflow rates. The other single air channel collector had fiberglass as the cover plate, corrugated metal roofing as the absorber, and chipboard as the back plate.

The remaining four rectangular shaped collectors had suspended absorber plates. One collector incorporated clear polyethylene film as the cover plate, black polyethylene film as the absorber, and plywood as the back plate and sides. Another collector had a glass cover plate, corrugated metal roofing as the absorber, and insulation and plywood for the back plate and sides. The third collector incorporated corrugated fiberglass as the cover plate, deep grooved formed metal as the absorber, and insulation and plywood for the back plate and sides. The remaining collector had two cover plates. The top cover was corrugated fiberglass and the lower cover was mylar film. The absorber plate was deep grooved formed metal and the back plate and sides were insulation and plywood.

COLLECTOR EFFICIENCY

Solar collector efficiency is defined as the actual useful energy collected divided by the solar energy incident upon the surface of the collector. In the tests the incoming solar radiation was measured by a pyranometer displayed at the fixed angle and adjacent to the collector surface to measure the amount of energy intercepted by the collector.

The incident solar energy recorded was an integrated value taken at six-minute intervals. Collector efficiency obtained during noon hour runs may also be referred to as "instantaneous" efficiency.

For full day runs, an overall collector efficency was obtained. The overall collector efficiency is defined as the actual useful energy collected during a day divided by the solar energy incident upon a fully tracking surface during the day. The overall collector efficiency denotes the amount of energy collected in comparison to the total amount of energy available at a location. The overall efficiency is useful in comparing flat plate collector performance with tracking and concentrating type collectors.

COLLECTOR PERFORMANCE

The pilot scale collector test results are summarized for noon hour operation, Figure 1, and for full day operation, Figure 2. Noon-hour collector efficiencies ranged from 14 to 89%. Lowest efficiencies were observed for bare collectors (without cover plate). Highest efficiencies were observed for suspended plate collectors with insulated back plates. The overall collector efficiency for full days of operation ranged from 11 to 57%.

Solar collector performance at different airflow rates is shown in Figure 3. The collector efficiencies for the rectangular shaped collectors were observed during noon hour runs. The airflow rate ranged from 2 to 16 cubic feet per minute per square foot of collector suface area. Collector efficiency increased with an increase in airflow rate.

Collector performance enhancement using planar reflectors is shown in Figure 4. The flat reflector surfaces were mounted on each side of the collectors. The reflectors were plywood or chipboard covered with aluminum foil. The results shown are with each reflector surface at an angle of 112 1/2^{o} from the collector surface or an included angle between reflector surfaces of 45^{o}. The results with reflectors show a larger boost in performance for the lower efficiency collectors.

RESULTS AND DISCUSSION

For the high performance collectors, energy collected for grain drying on sunny days approximated 1500 BTU per day per square foot of collector surface area. A typical fall drying period in the Western Corn Belt has sky conditions made up of 35% clear, 25% partly cloudy, and 40% cloudy skies. For such a fall drying period, energy collected for grain drying by the high performance collectors approximated 950 BTU per day per square foot of collector surface area.

SOLAR COLLECTOR EFFICIENCIES
NOON HOUR

FALL-WINTER, 1976-77
44 DAYS
CLEAR & PARTLY CLOUDY

SOUTH FACING
OPTIMUM ANGLE
AIR FLOW - 8 CFM/FT^2

	COLLECTOR				COLLECTOR EFFICIENCY %
SHAPE	AIR CHANNELS	COVER PLATE	ABSORBER	BACK PLATE	
	1	POLY	POLY	GROUND	42
	2	POLY	POLY	POLY	43
	1	BARE	METAL	PLYWOOD	14
	1	FIBER GLASS	PLY-INSUL	(W/REFLECT)	42
	2	FIBER GLASS	CHIP-BOARD	CHIP-BOARD	51
	2	POLY	13" DIA. PIPE	BLACK FELT	48

FIGURE 1. SOLAR COLLECTOR PERFORMANCE FOR NOON HOUR OPERATION.

SOLAR COLLECTOR EFFICIENCIES
NOON HOUR

FALL-WINTER, 1976-77
44 DAYS
CLEAR & PARTLY CLOUDY

SOUTH FACING
OPTIMUM ANGLE
AIR FLOW - 8 CFM/FT^2

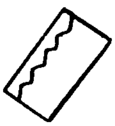
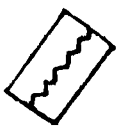
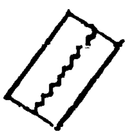
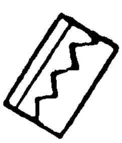
		COLLECTOR			
SHAPE	AIR CHAN-NELS	COVER PLATE	ABSORBER	BACK PLATE	COLLECTOR EFFICIENCY %
	1	BARE	METAL	PLYWOOD	22
	1	FIBER GLASS	METAL	CHIP-BOARD-INSUL	68
	2	POLY	POLY	PLYWOOD	62
	2	GLASS	METAL	PLY-INSUL	75
	2	FIBER GLASS	DEEP-V METAL	PLY-INSUL	82
	2	FIBER GLASS & MYLAR	DEEP-V METAL	PLY-INSUL (W/REFLECT)	89

FIGURE 1 (CONTINUED). SOLAR COLLECTOR PERFORMANCE FOR NOON HOUR OPERATION.

SOLAR COLLECTOR EFFICIENCIES
FULL DAY

Fall-Winter, 1976-77
29 Days
Clear & Partly Cloudy

South Facing
Optimum Angle
Air Flow - 8 cfm/ft^2

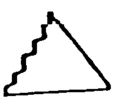
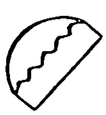
Shape	Collector: Air Channels	Collector: Cover Plate	Collector: Absorber	Collector: Back Plate	Coll Eff %	Orient Factor	Over-All Coll Eff %
	1	POLY	POLY	GROUND	43	.46	20
	2	POLY	POLY	POLY	40	.69	27
	1	BARE	METAL	PLYWOOD	16	.69	11
	1	FIBER GLASS	PLY-INSUL	(W/REFLECT)	41	.68	28
	2	FIBER GLASS	CHIP-BOARD	CHIP-BOARD	51	.66	34
	2	POLY	13″ DIA. PIPE	BLACK FELT	42	.66	28

Figure 2. Solar collector performance for full day operation.

SOLAR COLLECTOR EFFICIENCIES
FULL DAY

FALL-WINTER, 1976-77
29 DAYS
CLEAR & PARTLY CLOUDY

SOUTH FACING
OPTIMUM ANGLE
AIR FLOW - 8 CFM/FT^2

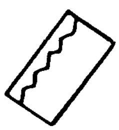
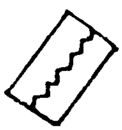
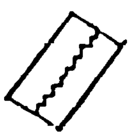
SHAPE	AIR CHAN-NELS	COLLECTOR COVER PLATE	ABSORBER	BACK PLATE	COLL EFF %	ORIENT FACTOR	OVER-ALL COLL EFF %
	1	BARE	METAL	PLYWOOD	23	.67	16
	1	FIBER GLASS	METAL	CHIP-BOARD-INSUL	63	.71	45
	2	POLY	POLY	PLYWOOD	55	.69	38
	2	GLASS	METAL	PLY-INSUL	68	.68	46
	2	FIBER GLASS	DEEP-V METAL	PLY-INSUL	76	.68	52
	2	FIBER GLASS & MYLAR	DEEP-V METAL	PLY-INSUL (W/REFLECT)	83	.68	57

FIGURE 2 (CONTINUED). SOLAR COLLECTOR PERFORMANCE FOR FULL DAY OPERATION.

SOLAR COLLECTOR EFFICIENCIES AT DIFFERENT AIRFLOW RATES

FALL-WINTER, 1976-77
CLEAR & PARTLY CLOUDY

SOUTH FACING
OPTIMUM ANGLE

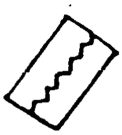
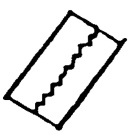
COLLECTOR					COLLECTOR EFFICIENCY, %			
					AIRFLOW RATE CFM/FT^2			
SHAPE	AIR CHAN-NELS	COVER PLATE	ABSORBER	BACK PLATE	2	4	8	16
	1	BARE	METAL	PLYWOOD	4	15	21	37
	1	FIBER GLASS	METAL	CHIP-BOARD-INSUL	31	48	68	76
	2	POLY	POLY	PLYWOOD	22	39	63	84
	2	GLASS	METAL	PLY-INSUL	35	52	77	81
	2	FIBER GLASS	DEEP-V METAL	PLY-INSUL	41	59	83	90
	2	FIBER GLASS & MYLAR	DEEP-V METAL	PLY-INSUL (W/REFLECT)	46	69	94	94

FIGURE 3. SOLAR COLLECTOR PERFORMANCE AT DIFFERENT AIRFLOW RATES.

SOLAR COLLECTOR EFFICIENCIES USING PLANAR REFLECTORS

FALL-WINTER, 1976-77
NOON HOUR
CLEAR & PARTLY CLOUDY

SOUTH FACING
OPTIMUM ANGLE
AIR FLOW - 8 CFM/FT^2

	COLLECTOR					
SHAPE	AIR CHANNELS	COVER PLATE	ABSORBER	BACK PLATE	COLLECTOR EFFICIENCY %	REFLECTOR BOOST FACTOR
	1	FIBER GLASS	PLY-INSUL		30	
	1	FIBER GLASS	PLY-INSUL	(W/REFLECT)	42	1.40
	2	FIBER GLASS & MYLAR	DEEP-V METAL	PLY-INSUL	68	
	2	FIBER GLASS & MYLAR	DEEP-V METAL	PLY-INSUL (W/REFLECT)	89	1.30
	2	FIBER GLASS	DEEP-V METAL	PLY-INSUL	82	
	2	FIBER GLASS	DEEP-V METAL	PLY-INSUL (W/REFLECT)	99	1.20

FIGURE 4. SOLAR COLLECTOR PERFORMANCE USING PLANAR REFLECTORS.

INFLATED PLASTIC STRUCTURES FOR SOLAR DRYING OF GRAIN

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Each fall corn growers attempt to balance the ever increasing field loss against the high cost of dry, early harvested corn. Cost and availability of grain transportation and storage must enter this decision, as does fluctuating weather and grain price. As energy and capital costs increase, we need to look at creative solutions to this problem.

Plastic film has been used to protect harvested grain from rain and snow. It has also been used as a solar collector to heat air to dry grain in conventional bins. This paper reports an on-farm attempt to combine these uses into an inflated solar grain dryer and storage structure.

Starting on September 24, 1977 I constructed a low-cost solar grain dryer. First, a layer of 6 mil black plastic was placed on the ground at the edge of my corn field. The ground was sloping to provide water drainage. Recycled shipping pallets, some in poor condition, were placed on the plastic about 4" apart. Next, light-weight plastic netting resembling one-quarter inch hardware cloth was placed over the pallets. Used power poles were placed on the edge of the pallets to form a rectangle 25' x 94'. At one end the power pole was supported by posts 2' high and a plywood wall was constructed under it. A 2' x 2' access door and the discharge ducts from the squirrel cage fans were installed in this wall.

The grain was dumped directly from the combine to form a free standing stack. The stack was almost 5' deep at the center and filled an area 25' x 84' and contained about 3,400 bushels.

To form an air control valve a 6' wide sheet of black plastic was centered over the pole which laid on the pallets. By sealing the outside edge of this valve to the ground air escape could be selectively stopped. This plastic valve extended under the grain about 2' around the edge where the grain was not deep.

Reinforced clear plastic was then attached to the power poles using 2" x 2" nailing strips. The plastic was puckered at the corners to avoid stress points. When the fans, which were powered by a gasoline motor, were started, the house was inflated to form a parabola 10' high in the center.

The fans produced about one-fourth inch of water pressure which held the plastic roof up and at the same time forced air through the grain. The sun's rays passed through the plastic and warmed air as it was forced down through the grain, into the duct formed by the pallets, and was discharged to the outside. The motor and fans were sheltered by clear plastic supported by a simple frame. This shelter caused the intake air to be drawn over the gasoline engine thereby collecting the waste heat of the engine.

Ten feet of the house which was not filled with grain added to the solar collection area. The total solar collection area was 25' x 94' or 2,350 square feet. One researcher in Kansas calculated that a square foot could be equal to .186 kilowatts. At 2.6 cents per kilowatt this amounts to $11.12 per day.

The fan was on for 32 days between October 10 and November 19, 1977. Based on the fans ratings I estimated 4,000 cu. ft. per minute of air passed through the grain. The moisture content of the grain was 22.5% when the fans were started and dropped to 17.5% by November 19, 1977. The grain dried in the shallow areas first. Therefore, these areas were covered with black plastic to prevent air from moving through these dry areas.

On October 1 the first load of corn dumped into the dryer was covered with plastic without air for ten days. Condensation of the underside of the plastic caused the kernels on the surface to sprout and mold to form. Four bushels of moldy and sprouted corn were removed and used as cattle feed. The rest of the molded corn was distributed across the surface of the stack where it quickly dried without further deterioration.

The gasoline engines used have proved unreliable and the air supported structure has deflated over 20 times. Wind pulled the plastic free from the power poles and ripped it on two occasions. Repairs were made. Wind never damaged the structure while the fans were operating. Electric power would decrease engine failure which was the most serious problem encountered.

The costs of this dryer are as follows. The plastic roof, made of a reinforced clear sheet, 32' x 100', cost $170.95. The plastic one-fourth inch hardware cloth cost just over one cent per square foot or $36.64. Other plastic came to $59.30. Nails, tape, rat bait and starter fluid added $15.73. Gas and oil for the engine powering the fans cost $117.73. These expendable and short-lived items total $400.35 or 12.4 cents per bushel. The power poles cost 30 cents per foot or $72.80. The 9 hp engine was $202.49. The three fans, one new and two used, cost $52.00. Pulleys, belts and hose clamps and lumber added $28.58. The total for capital items was $355.87 or 10.5 cents per bushel. Total cost for drying and storage was 22.9 cents per bushel. Gas and oil contributed less than 3 cents per bushel, indicating an energy efficient system.

My plans called for the grain to be sold around January 1, but snow drifts limited access to the dryer which was one-fourth mile from the road. As mentioned earlier, when the fan failed during a storm, two rips developed in the plastic cover. These were patched, but snow later blew in these holes. After the fans were turned off and the plastic weighted down with old tires, snow may have also blown under the dryer, wetting the stored corn along the edge of the dryer. The snow was so deep that a calf walked across the dryer (without causing damage). However, wild rabbits tunneled into the snow drifts and cut the plastic. A few mice were noted, but rats were not a problem, suggesting the rat bait was effective.

When the dryer was unloaded on April 1, 1978, small amounts of moldy grain were discovered in the two places where the plastic had been ripped by high winds. Mold was also found where wild rabbits had cut through the plastic cover, allowing some moisture to enter. However, by far the largest amount of spoilage and high moisture grain was found on top of the plastic sheet used as an air control valve that extended about 2' over the plastic netting all the way around the edge of the structure.

The one area where mold was never found was at the center under the deepest part of the stack, just over the netting where the moist air exited. Therefore, most grain damage occurred near the edges where the grain dried fastest, dropping to 14% soon after the fans were started. Therefore, this damage was from rewetting by snow drifting under the dryer, or possibly by condensation collecting on this plastic. The plastic netting functioned well in that it supported the grain and did not trap melting snow or condensation.

The dryer was unloaded with a light weight auger. The auger was set into the grain where it worked itself down to the pallets. The elevator was moved frequently and grain was shoveled to it by hand. Three men loaded all the grain in less than 10 hours. Grain that could not easily be shoveled off the pallets was left to feed my cattle. The plastic sheeting under the pallets enabled me to retrieve every last grain by lifting one edge of the plastic to roll the grain into piles.

It cost 23 cents per bushel to construct and operate this dryer which reduced the moisture in the corn from 22.5% to 17.5% by mid-November. On April 1, 1978, when it was sold, it tested 18.3% moisture, indicating some rewetting had occurred.

Was the dryer an economic success? The local grain price when the dryer was filled was $1.48 per bushel. The same elevator was offering $1.88 per bushel if delivery was delayed until after January 1 or 40 cents per bushel for storage alone. Using the elevator's standard shrinkage value of 1.3% for each 1% of moisture, I had 3,231 bushels of grain at 22.5% moisture at harvest and sold 3,131 bushels of 18.3% moisture on April 1. The price on April 1 ranged from $2.31 to $2.33 per bushel.

At harvest, my 3,397 bushels of corn at 22.5% moisture, with a base price of $1.48 per bushel would have netted $1.20 per bushel or $4,077. On April 1, I sold 3,231 bushels of corn at 18.3% moisture containing 12.19% damage on a $2.31 to $2.33 per bushel market for $6,832., or $2.11 net per bushel. My gross improved by $2,755 or 85 cents per bushel sold. Had I sold at harvest for delivery after January 1 and delivered corn at 17.5% moisture with no damage, I would have received 60 cents per bushel more than I would have obtained for my corn at harvest. This value of 60 cents per bushel is probably a better value to set on the gross earning of the structure.

The labor required to build, operate and inspect this structure has not been recorded for much of it has been in design and sampling. Keeping the gasoline engine operating required substantial labor also.

This dryer aided harvest as no labor was used to transport grain at harvest time. I own a corn combine, but find grain trucks hard to rent at harvest.

SUMMARY AND CONCLUSIONS

I designed a solar grain dryer that required $756.22 to build and operate. The grain dried in it suffered some damage, but sold for $2,755.00 more than it would have at harvest for a return to design, labor and management of almost $2,000.00. Had it been sold in January before the damage occurred, it would have sold for about $800.00 less. The labor required to load the grain out of the dryer is partly offset by not having to rehandle grain from the combine at harvest time when labor and trucks are in short supply.

RECOMMENDATIONS

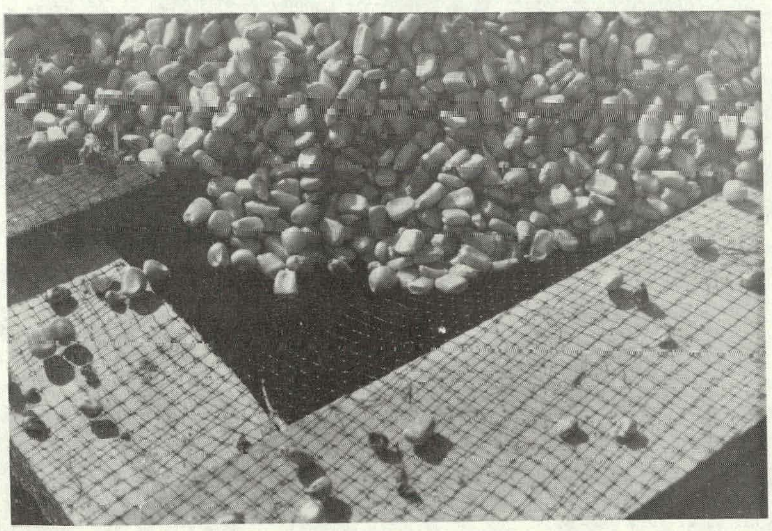
1. The design should be modified to provide for vertical side walls 3' to 6' high and the grain should be piled to a nearly uniform depth to promote uniform drying.

2. Plastic should never be placed directly under the grain.

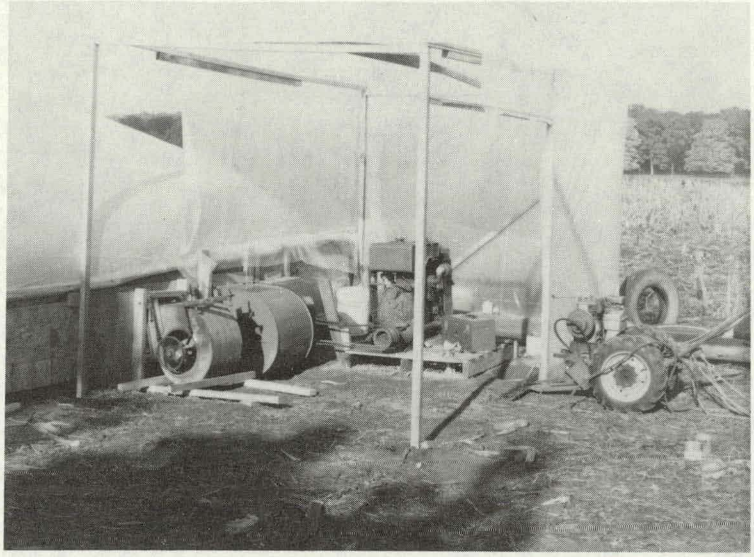
3. Use electrically powered fans, as small gasoline engines are unreliable.

Piling grain directly from the combine by attaching a trough to the grain auger.

Pallets covered with plastic netting support the grain and provide an air duct to exhaust air that has been forced down through the grain.

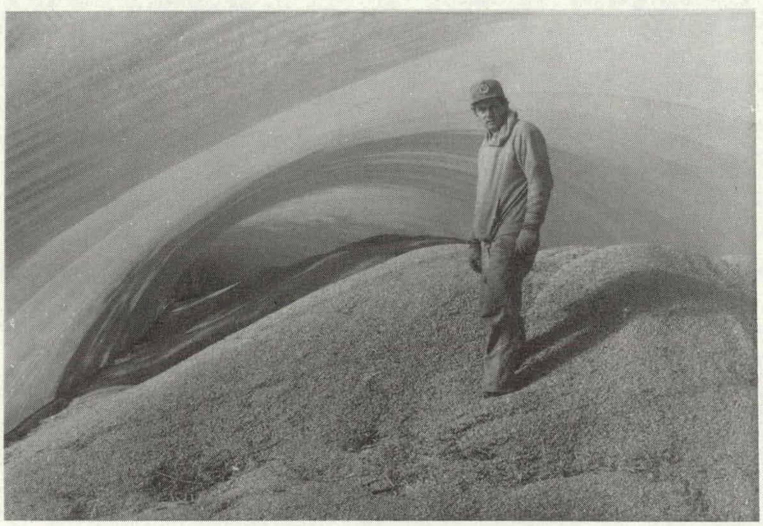


Plastic netting with 1/4 inch holes supporting grain on pallets.



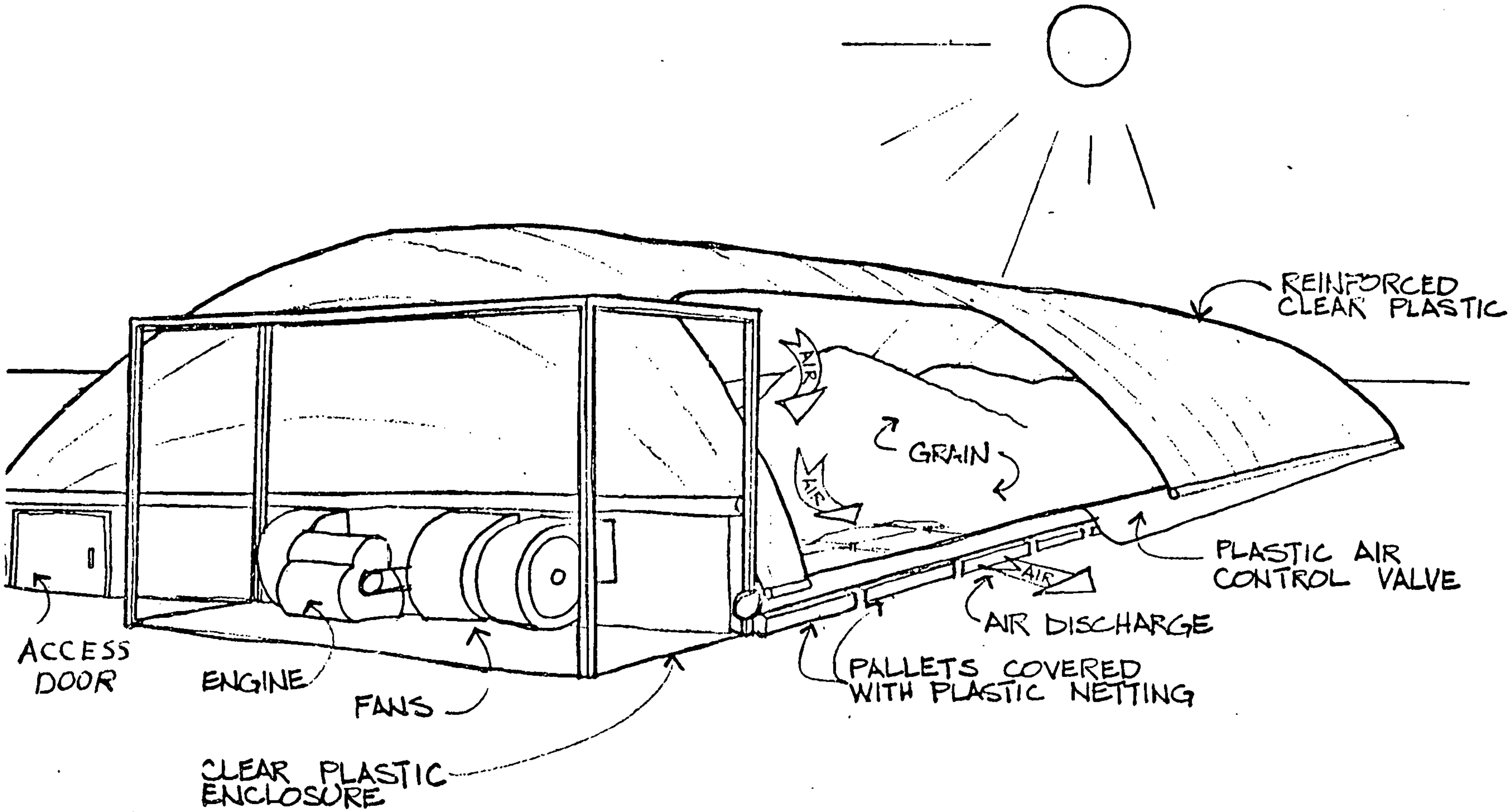
Fans and engine protected by a clear plastic covered structure.

The reinforced plastic cover protects the grain from rain and snow, and allows solar energy to pass through.



Air pressure supports the reinforced plastic and forces the air down through the grain.

Unloading the dryer
April 1, 1978


REINFORCED CLEAR PLASTIC.
AIR
AIR
GRAIN
AIR
PLASTIC AIR CONTROL VALVE
AIR DISCHARGE
PALLETS COVERED WITH PLASTIC NETTING
ACCESS DOOR
ENGINE
FANS
CLEAR PLASTIC ENCLOSURE

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DRYING GRAIN WITH AIR FROM A SOLAR HEATER DESIGNED FOR ANIMAL SHELTERS

Ralph Lipper, John Anschutz, and C. K. Spillman*
Agricultural Engineering Dept., Kansas State University
Manhattan, Kansas

The U.S. Department of Energy's research program on direct use of solar energy includes applications related to animal production. At Kansas State University, Dr. Charles Spillman is demonstrating a successful design of a solar collector-storage wall to pre-warm ventilation air for animal shelters. Application of the research unit at Manhattan is to a swine farrowing house. The design is ideally suited for dual use in grain drying.

We have long known that dry time and electrical energy use could be reduced by supplementing natural air drying potential with solar energy. But, cost effectiveness has been difficult to demonstrate where collectors are used only for short-time application to grain drying.

In two and one-half years of observations, the research solar collector-storage wall on the farrowing house has demonstrated that it can be justified economically when used for that purpose alone. Five such units now have been incorporated into new swine production buildings on commercial farms. Data have been taken on two of them through two winters and two were used during the winter of 1978. They are performing very well.

DESCRIPTION OF THE KSU FARROWING HOUSE SOLAR COLLECTOR-STORAGE WALL

A wall (8' x 50') with net collector area of 380 sq. ft., 16" thick, constructed of solid concrete blocks with the south side painted black serves as the collector-storage unit. The wall is set 16" out from and parallel to the existing, lightly insulated south wall of the farrowing house. The blocks were laid up without mortar, but mortar in horizontal joints for greater ease of construction is being recommended for future plans. Gaps in vertical joints provide an opening for air to move through the wall. The wall contains about 31 tons of blocks. They were delivered to the site for less than $18.00 per ton. Random sized field stone had been quoted at $32.00 per ton.

A double transparent collector cover on a frame is constructed to allow air to enter at top and bottom between the covers, pass through a 1" wide horizontal slot at mid-height in the inner cover and then diffuse over the collector wall surface and through the blocks (Figure 1). Space between covers, and between inner cover and wall, is about 1 1/2". The inner cover and half the outer cover is 4-mil TEDLAR film. The other half of the outer cover is rigid, glass-reinforced resin sheets.

A centrifugal fan moves air through a duct from the 16" x 8' x 50' plenum formed by the space between the building wall and the collector-storage wall to a furnace inside the building. The propellar-type fan shown in Figures 1 and 2 is only for illustration. As constructed, the building can be ventilated without drawing any air from the collector.

The KSU facility has been fully instrumented with two pyranometers, digital data logger, strip-chart recorder with integrator, many thermocouples, 5" ASME long radius nozzle, and micro-manometer for determining collector efficiency, hourly air temperatures, ambient radiation and other data necessary for modeling performance of the system. The

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unit has been tested with air flows ranging from 0.75 to 6 cfm per sq. ft. collector area. Pressure drop through the wall at the highest rate was 0.225 in. of water. To date, complete data have been taken on air flow rates up to 1.75 cfm per sq. ft. (700 cfm total). At that rate, in October 1977 the 24-hour average temperature rise on a clear day was 20° F with total usable heat production of 15,120 Btu per hr. and overall collector efficiency of 65%. Collector efficiency was only 42% with 0.75 cfm per sq. ft.

COLLECTORS ON COMMERCIAL SWINE HOUSING

In the newly built commercial houses, the concrete block collector-storage walls serve as the load-bearing building walls with solid plywood panels behind them for interior walls. In contrast to the KSU research unit in which the collector runs only half the length of the south wall, the collectors run full length. Space between walls varies from 4" to 6". The blocks are cooled during summer nights using motor-operated shutters, fans, and timers to force outside air through them in the reverse direction. With plywood covers over the collector faces, daytime ventilation air is then pulled through the blocks for cooling.

ADAPTATION OF THE COLLECTOR-STORAGE WALL FOR GRAIN DRYING

No changes were needed in the farrowing house system to supply solar warmed air for grain drying. A duct, 10 feet long, was connected to the east end of the KSU collector so that a grain drying fan can pull air through the collector and the wall, then lengthwise along the space between walls as illustrated in Figure 2. That duct is insulated. Parallel to that duct is an ambient air duct equipped with a damper so that air from the collector and ambient air can be mixed to give the desired temperature rise to air used for drying. The bin is an 18', 17'-diameter, 5,000-bushel bin with full perforated floor and bottom unloading-recirculating auger.

Delays in delivery of grain bin and accessories prevented completion of the drying facility in time to dry grain in the fall of 1978. However, performance of the KSU research collector is well documented and is being modeled for computer simulation of the system.

PLAN OF OPERATION

Based upon average weekly data on dry bulb temperature and wet bulb depression for 22 years at Manhattan, computations based upon the standard heat balance equation indicate that we should have been able to dry corn from 24% to 15% wb in the allowable time (0.5% dry matter loss) with natural air using 2 cfm/bu in all but one of those years. We will use a 2,000-bu charge in the bin and 4,000 cfm. We estimate that the solar storage on the farrowing house will sustain an average temperature rise of 3 to 4° F (in addition to 1.5° F from the fan motor) for a period of 24 hours or more for each sunny day. At the end of the drying season, we will layer dry to fill the bin to capacity for storage.

Rationale for selecting operation parameters is: The heat provided by the 380 sq. ft. solar collector-storage wall, even with its relatively good efficiency and with ground level reflector panels in place, will provide only enough heat in October to evaporate the moisture in about 60 bushels of corn (at 9 point moisture reduction) for each sunny day. Therefore, we propose to use the heat to attain only a 3 to 4° F temperature rise on ambient air to speed natural air drying and provide a margin of safety on years less favorable for natural air drying. That allows us to use the heat available on the greatest possible volume of corn. For example, using data for the median year in the 22 for which we compiled data, application of the heat balance equation shows that we could dry 1,000 bu using 2 cfm/bu with an average 8.5° F temperature rise (7.0 from collector, 1.5° F from motor) in 7.9 days for 127 bu/day. We could dry 2,000 bushels using 2 cfm/bu with an average 5° F temperature rise (3.5 from collector, 1.5 from motor) in 10.3 days for 193 bu/day.

CONCLUSION

The combination use of this solar collector-storage, heating-cooling wall should prove to be nearly ideal. Corn harvest in Kansas often can start as early as the middle of September. By then, need of the storage wall for swine cooling should be nearly over. The new swine confinement buildings built with this collector-storage wall are well insulated and require only moderate ventilation rates. Heating of ventilation air will not be required at the height of corn harvest season. By the time swine house heating is required, temperatures will be low enough for safe natural air cooling and drying of the grain.

ACKNOWLEDGMENTS

Cooperation of the following firms who donated equipment, construction supervision and labor to erect the grain drying system is greatefully acknowledged:

J & N Elliott Construction, Inc.
Morrowville, Kansas

Chief Industries Inc.
Grand Island, Nebraska

Shivvers Enterprises, Inc.
Claydon, Iowa

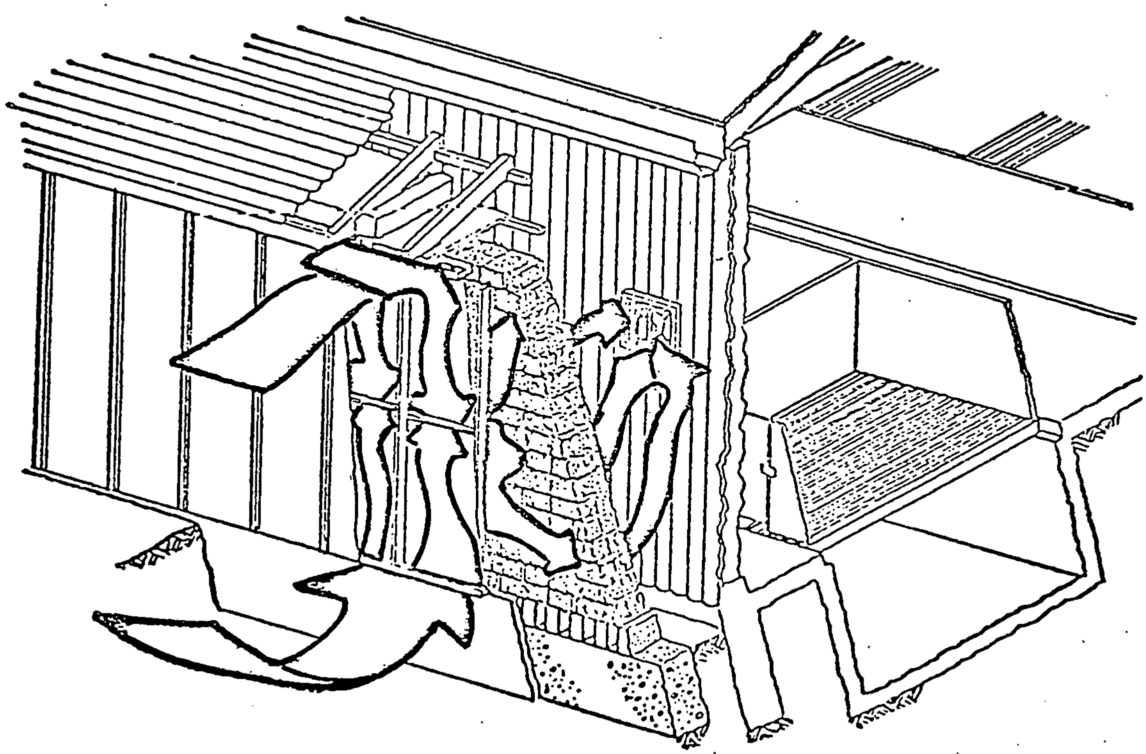

Figure 1. Arrows show the path air takes as it moves through the covers and blocks on its way to the fan.

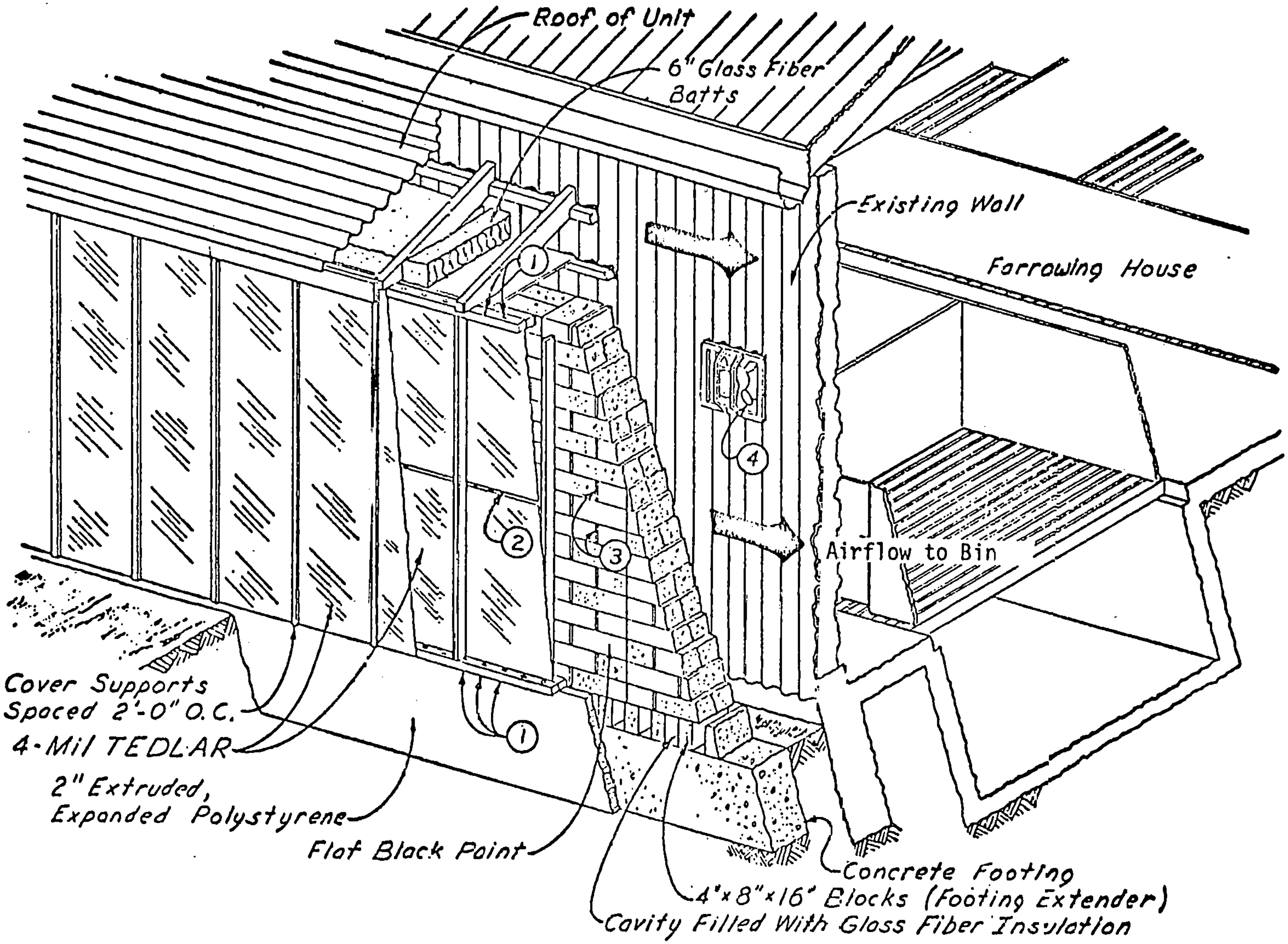

Figure 2. Details of construction of the solar collector-storage unit. Ventilating air moving through the system enters at point 1, moves between the covers to point 2, then through the vertical gaps between blocks, point 3, and to the fan where it is moved into the environmental space. Blocks used to lay up the wall are 6 x 8 x 16 solid concrete.

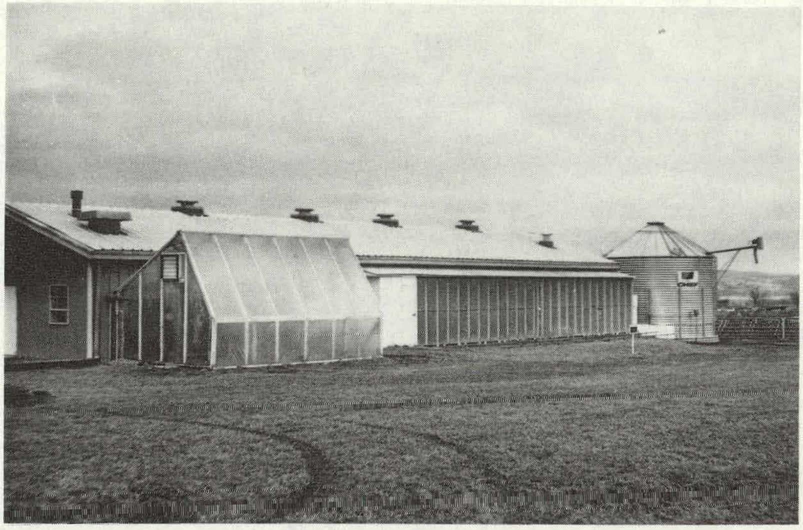

Figure 3. Kansas State University farrowing house, solar collector-storage wall, grain drying system and an experimental greenhouse warmed by exhaust air from the farrowing house.

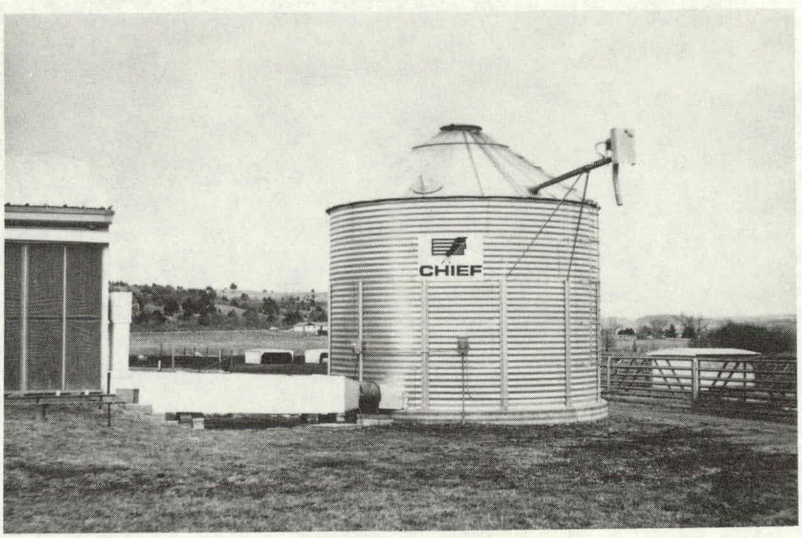

Figure 4. The solar grain drying system.

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SOLAR COLLECTORS INCORPORATED INTO AGRICULTURAL BUILDINGS TO COLLECT ENERGY FOR CROP DRYING

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SUMMARY

Agricultural buildings provide large areas of flat surfaces into which solar energy collectors can be incorporated. Walls and roofs constructed as flat plate collectors with only minor modification in building design helps reduce collector costs. Air is utilized as the heat transfer medium since agricultural crop drying is accomplished by moving air through wet grains and forages. Solar collectors on buildings are efficient, even though various air cavities are utilized, because the high airflows used in crop drying result in relatively high air velocities and small temperature differentials. In some situations the collectors can have a multiple use such as heating a repair shop or livestock shelter after the crop drying season. Therefore, the inclusion of collectors to collect solar energy for farmstead operations should be given serious consideration as existing buildings are remodeled or new buildings planned.

SOLAR BUILDINGS

Sheet metal roofing and siding commonly used in farm building construction become bare plate solar energy absorbers when some means is provided to move air along the back side. Dark colored sheets are preferred although galvanized metal has been utilized. Air cavities are created under roofs or behind walls by attaching a lining material to the structural supporting roof and wall members. The use of the building determines whether or not there is a need for lining material which offers resistance to heat transfer. If the building is to serve as a cold machinery storage shed, any loss of solar heat through the lining material can be recaptured by allowing air to move through the building before it enters the collector. However, if the building is to be used as a heated repair shop or as a livestock shelter, insulation should be used in conjunction with the lining to minimize heat losses.

Building surfaces become covered plate solar collectors when clear fiberglass is substituted for the outer metal covering. Black-surfaced paneling provides the energy absorbing surface and creates the air cavity. Even entire attics of buildings can be used as solar heat collecting chambers for grain drying systems. Since grain drying involves large volumes of air, relatively high air velocities can be maintained in the attic spaces; therefore, an attic space can be a reasonably efficient solar collector. The orientation of buildings with attic collectors is not critical since the solar absorbing surface is in a horizontal position. If the length of a gable roof building is oriented north-south, both the east and west roof slopes should have a cover of clear fiberglass. However, if the building is oriented east-west, it is only necessary to install clear fiberglass on the south roof slope. During the grain drying season in the major corn producing areas surrounding the 40 degree latitude, the angle of the sun will be such that most of the horizontal energy absorbing surface will be exposed to the sun's radiation through the clear south roof slope. Conventional metal roofing can be installed on the north roof slope.

COLLECTOR OPERATION

Since keeping solar collector temperature differentials at a minimum is beneficial to the efficiency of operation of collectors, it is desirable to move as much air as possible through collectors applied to crop drying. However, frictional losses in moving air through collectors and ducts connecting solar buildings to crop drying systems must be considered. The air volume output of most crop drying fans begins to diminish rapidly as the static pressure against which the fan must operate exceeds four inches of water column. If the solar collector system consumes more than approximately 20% of the pressure capability of the fan, the solar drying system may not have sufficient airflow for satisfactory drying. However, because of the high airflow used in crop drying, solar collector efficiency can be maintained without moving all the air through the collector. Frictional losses in the solar collection system can be adjusted to less than one inch of water column by installing a sliding door near the fan to divert a portion of the air directly to the fan, bypassing the collector and the connecting duct. While the system is in operation, an adjustment is made to keep the fan within a satisfactory operating range and yet maintain as high an airflow as possible through the collector.

SOLAR BUILDINGS DRY GRAIN

Additional information on the application of solar energy to grain drying is available in the proceedings of a 1977 conference (1) and recommendations for low temperature corn drying appear in a Food and Energy Council publication (2). Some data obtained on solar farm buildings supplying energy for crop drying is listed in Table I.

Table I. Air Temperature Rises and Power From Solar Collectors Incorporated Into Farm Buildings for Drying Grain in October and November

Collector Configuration	Area sq. ft.	Drying Fan kW	Air Temperature Rise, F Max.	Approx. 24-hr Ave.	Approx. Ave. Power, kW
Bare Plate					
South and north galv. metal roof, 3° slope[a]	1,500	10	11	2	6
Covered plate					
Vertical wall and complete attic[b]	4,500	10	30	6	15
Vertical wall and south roof, 20°slope [c]	1,400	20	16	4	20
Horizontal roof[c]	6,000	10	30	7	23
Wall at 60°angle [c]	288	5	14	4	4

a/ Located in Wisconsin at about 43° north latitude

b/ Located in Illinois at about 41° north latitude

c/ Located in Illinois at about 40° north latitude

Maximum air temperature rise achieved in a crop drying solar collector is an interesting value; however, it is the total energy collected that must evaporate moisture from the wet crops. Therefore, the energy (or air temperature rise) obtained during the daylight hours must be averaged over the entire 24-hour day. The daily solar energy collected can also be considered in terms of electric resistance heater wattage necessary to provide the same energy over a 24 hour period. Since crop drying generally continues for several days or a few weeks, it is even more appropriate to average the energy collected over the entire drying period. Thus, solar energy is well suited to low temperature grain drying which does take place over an extended period of time with small air temperature rises. The longer the period over which solar energy can be applied to a process, the more likely sufficient solar energy will be available. This is particularly true in an agricultural process, such as crop drying, which is tolerant of variable heat energy input.

Since crop drying can be functional with a variable heat energy input, it is not necessary to provide heat storage as a part of a solar drying system. Therefore, simple flat solar collectors incorporated into building surfaces without provision for heat storage can be cost effective for supplying heat energy for the drying of agricultural crops.

Justification of an investment in a solar building is even more feasible if multiple use can be made of the collector. Farm buildings provide this opportunity, i.e., a solar collector incorporated into a livestock building for grain drying purposes can provide heat for the building itself during winter months following the grain drying season. Machinery storage solar buildings constructed primarily to collect heat for drying grain can also provide heat in winter for repair shops in, or adjacent to, the machine shop building.

SOLAR BUILDINGS IN ILLINOIS

A swine building, 42 ft. wide by 184 ft. long, with a dark green metal gable roof is used as a bare plate solar collector to provide heat for drying grain in Marshall County, Illinois. Air is channeled along the underneath side of the dark-colored roof and then moved through a 3 ft. diameter underground culvert to two 15,000 bu. grain drying bins. At each bin a 20 kW centrifugal fan pulls air out of the culvert and forces it through shelled corn. A sliding door in the side of each fan enclosure provides a means of regulating airflow through the solar roof of the swine building. With both sliding doors closed, approximately 36,000 cfm of air would be moved through the solar roof. The sliding doors are adjusted with the fans in operation to limit the static pressure drop through the solar roof and duct system to not more than about 0.8 inch of water column. The doors also provide a maintenance access to the fans. During the winter separate fans move ventilation air through the roof collector before it is blown into the building. The solar air cavity on this swine building was created by laying 3/4 inch thick urethane foam insulation boards on the top of 2 x 4 inch purlins on edge running the length of the building. On top of the insulation boards 2 x 2 inch wood members support the dark-colored metal roof sheets.

In Vermilion County, Illinois, the nearly horizontal roof of a rigid steel frame 70 x 90 ft. machinery storage building was converted to a covered plate solar collector by installing clear fiberglass over black painted plywood. The ½ inch plywood is supported on the lower ledge of 5.5 inch steel purlins, creating a solar cavity with a depth of 5.5 inches. Air is ducted from the 6,000 sq. ft. roof collector through a 48 ft. long triangular solar collector duct which provides an additional 300 sq. ft. of collector surface. Air is moved through the solar system by a 10 kW axial-flow fan installed on a grain drying bin equipped with a gas heater and a grain stirring machine. The system is operated as a solar energy grain drying facility or as a combination solar energy-gas energy facility. The solar roof is also used for winter heating a small shop located inside the building. In 1976 the additional cost of constructing the building with a solar roof instead of a conventional steel roof was between $6,000 and $7,000.

A machinery storage building utilizing the south wall and the attic space as a covered plate solar collector for drying grain is in operation in Livingston County, Illinois. Air is moved up the fiberglass-covered wall and into the attic. The gable roof building is oriented east-west with a fiberglass covering on the south roof slope and a metal roof covering on the north roof slope. During the October-November corn drying season, radiation from the sun entering through the clear south roof slope strikes a large portion of the horizontal black attic floor. A grain drying fan located 99 ft. from the building draws air through this solar building. A 99 ft. duct will offer considerable resistance to airflow unless it has a relatively large cross sectional area. Adjustment of airflow through the solar system can relieve the pressure loss but may lower airflow below that required for maximum solar energy collection. This situation suggests that whenever possible advance planning should be made regarding the location of solar buildings in relation to grain drying facilities. A shop in the west end of this machine shed has a concrete floor placed over crushed rock. During the winter a small fan circulates solar heated air from the attic collector through the rock to warm the shop floor. Solar heated air can also be circulated through the shop space.

In Macon County, Illinois, a suspended plate solar collector grain drying building has a grain storage capacity of about 40,000 bu. Metal sheets attached to the south curvature of a 40 x 100 ft. self-supporting steel arch building were painted black to form the solar energy absorbing plate. A cover of clear, corrugated fiberglass completes the collector. Air enters the collector along the entire top length of the building and moves down through the curved collector on both sides of the energy absorbing plate. The curved surface provides approximately 3,000 sq. ft. of suspended plate collector surface. An additional 1,000 sq. ft. of clear fiberglass forms an enclosure along the length of the building housing three 20 kW centrifugal fans. The solar heated air is distributed to wet corn by removable, on-the-floor ducts across the width of the building. This allows the building to be used for other purposes when not being used to dry or store grain.

A solar hay drying building is operating in Clinton County, Illinois. A 45 x 145 ft. hay storage building has approximately 10,000 sq. ft. of solar collector surface built into its roof and south wall. Both the south and north roof slope is utilized as solar collector surface since much of the hay drying is done during the time when the sun is more directly overhead. Nine 5 kW fans, each connected to separate ducts formed in the concrete floor, pull air through the roof and wall cavity. The solar heated air is then forced through large round bales of hay placed on grates built into the air ducts. Each 5 kW fan and its accompany duct is a separate system serving four bales of hay providing flexibility in the number of bales that need be dried at any one time.

ECONOMIC DATA AND PLANS AVAILABLE

A recent economic study by Heid (3) suggests that solar drying of corn may be economically feasible. Given current cost comparisons, a solar drying system might be considered if an additional dryer is needed, if a conventional dryer needs replacing, or if fossil fuels are no longer available. Heid also stated little is known about whether a total solar drying system or a combination solar-aeration, solar-electric or solar-fossil fuel dryer is best for a particular climate. Regardless of the uncertainties that still exist and lack of complete decision making information in relation to solar grain drying facilities, grain producers are constructing solar buildings. As an aid to solar building construction the University of Illinois has made available the following plans:

Illinois Plan No. SP 543 — 4 pages — $2.00
50' MACHINE STORAGE AND SHOP WITH ATTIC SOLAR COLLECTOR

This 50' by 96' pole machine shed has a 50' by 32' shop and office section. A clear fiberglass roof allows for the entire attic space to serve as a solar collector. Heat storage is accomplished with 2 feet of rock under the shop and office. Specifications for use in grain drying are included.

Illinois Plan No. SP 544 — 4 pages — $2.00
50' MACHINE STORAGE AND SHOP WITH WALL AND ATTIC SOLAR COLLECTOR

This 50' by 120' pole machine shed has a 50' by 32' shop area. The south wall and the attic serve as a solar collector. Heat storage is accomplished with 1 foot of rock under the shop and office. Insulation is used to reduce heat storage losses. Specifications for use in grain drying are included.

Illinois Plan No. SP 545 — 4 pages — $2.00
50' MACHINE STORAGE AND SHOP

This 50' by 96' pole machine shed has a 50' by 32' shop and office. The roof purlin space acts as the solar collector. Either metal or clear fiberglass roofing may be used. Specifications for use in shop heating, heat storage, and grain drying are included.

Illinois Plan No. SP 546 — 2 pages — $1.00
PORTABLE SOLAR COLLECTOR

This 12' high by 24' long collector is designed at a 60^{o} slope. Air is the energy transfer medium although water could be heated with the addition of plumbing. A rock storage area is provided. This solar collector can be moved.

Illinois Plan No. 562 (Revised) 2 pages $1.00
26 SOW SOLAR VENTILATED FARROWING HOUSE

This 26' by 80' farrowing house contains 26 farrowing crates, an isolation pen and an office. The entire roof serves as a solar collector to warm the incoming ventilation air when the sun is shining. During hot weather the solar collection duct is closed off and air is pulled directly from the outside. Any type of slotted floors can be used over the pit.

Illinois Plan No. SP 547 11 pages $5.00
32' SOLAR HEATED FARROW-TO-FINISH HOG UNIT

This 32' by 226' farrow-to-finish hog unit with an 8 ft. full pit has a 56 ft. farrowing section with 30 farrowing crates, a 50 ft. nursery section with 15 pens (5' by 7') and a 120 ft. growing-finishing section with 15 pens (13' by 8') and 13 pens (17' by 8'). The entire roof serves as a solar colletor to warm the incoming ventilation air when the sun is shining. Side doors are provided for natural ventilation during hot weather.

Illinois Plan No. SP 548 9 pages $4.00
48' SOLAR HEATED FINISHING BUILDING

This 48' by 80' finishing building can be expanded by adding additional 80 ft. sections. A clear fiberglass roofing allows the sun to warm the entire attic space which supplies all the ventilating air. Side doors are provided for natural ventilation during warm weather. Each 80 ft. section has an off center aisle resulting in two rows of 10 pens 8 ft. wide which are 19 and 25 1/2 ft. long. The floor has full concrete slats.

Illinois Plan No. SP 549 11 pages $5.00
44' SOLAR HEATED FARROW-TO-FINISH HOG UNIT

This 44' by 272' farrow-to-finish hog unit has an 88 ft. gestation section, a 48 ft. farrowing section (32 farrowing crates), a 40 ft. nursery section and a 96 ft. finishing section. A full pit, 8 ft. deep is provided for manure storage. Colored steel roofing serves as a solar collector. Side doors are indicated for natural summer ventilation in the gestation, nursery, and finishing section. The farrowing section has a summer ventilation duct with air piped to each sow.

Order plans from:

Department of Agricultural Engineering
University of Illinois
Urbana, IL 61801

Make checks payable to: "Agricultural Engineering"

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1. Shove, Gene C. (Editor), "Solar Grain Drying Conference Proceedings", National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, CONF-77140, October 1977.

2. Shove, Gene C., "Efficient Energy Management With Low Temperature Grain Drying", Food and Energy Council, Columbia, Missouri, November 1976.

3. Heid, Walter G., Jr., "The Performance and Economic Feasibility of Solar Grain Drying Systems", Commodity Economics Division, Economics, Statistics, and Cooperatives Service, U.S. Department of Agriculture, Washington, D.C., Agricultural Economic Report No. 396, February 1978.

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LOW TEMPERATURE, LOW AIR FLOW SOLAR DRYING OF CORN WITH AND WITHOUT STIRRING

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INTRODUCTION

Results from a simulation study by Morey, et al. (1977) indicate that in most cases, it is not feasible to use strictly low temperature drying methods for corn at moisture contents above 22-24 percent. They also show that using supplemental solar heat generally reduces the air flow rate 10 to 15 percent from that required for ambient air drying, especially for central Indiana. In the same study, an economic analysis shows that conditions are most favorable for solar drying with initial moisture contents of 20-22 percent. In late fall in Indiana, the weather conditions are often such that complete drying of a bin of corn with ambient air is not possible and drying must be completed in the spring. Supplemental solar heat increases the probability of finishing the drying operation in the fall. Based on this information, a system using a high temperature dryer to reduce the moisture content of corn to 20-22 percent combined with a bin dryer with supplemental solar heat and minimal air flow rate to finish the drying operation appears feasible.

Use of supplemental solar heat may lead to increased overdrying of grain at the bottom of the bin before the drying front moves through the top layers of grain. Use of a vertical stirring auger helps maintain a uniform moisture content throughout the bin (Peart, 1977) and reduces overdrying. Stirring also reduces the moisture of the top layers of grain more quickly and extends allowable drying time before critical microbial deterioration occurs.

OBJECTIVES

One objective of the solar grain drying tests at the Purdue Agronomy Farm in the fall of 1977, was to determine feasibility of utilizing solar energy for the low temperature phase of a combination high temperature-low temperature drying system. In this system, corn is put into the solar bin from the high temperature dryer at a moisture content of 20-22 percent. The lowered moisture content allows a longer drying time before microbial deterioration occurs and permits the air flow to be reduced in the low-temperature drying phase. This reduction in air flow decreases fan and collector size required to maintain the same temperature rise. Thus, investment costs are significantly reduced.

A second objective of these tests was to evaluate use of vertical stirring augers in bin drying systems using solar energy. Stirring prevents overdrying of bottom layers of grain, provides more uniform drying throughout the bin and reduces moisture content in the top layers of grain more quickly. However, the rate of drying may be reduced when stirring is used because moisture content of the top layers of grain is reduced, thereby reducing the extent of saturation of drying air leaving the grain and the energy utilization efficiency. This effect was also evaluated.

EQUIPMENT AND LAYOUT

A flat plate collector was designed for the tests. The collector was mounted on skids to make it portable, so that it could be used for other purposes. The collector panel was hinged on one side and supported by adjustable steel pipes so that the tilt angle of the collector was adjustable from 30° to 50°. The cover plate was greenhouse grade corregated fiberglass and the absorber plate was corregated sheet metal painted flat black. The absorber plate was suspended and air moved across both sides. An inch of styrofoam insulation was glued to the plywood backing. The collector was built in 12 ft. by 16 ft. sections. Two or more sections could be joined together if a larger collector area was desired. Commercially available materials were used and the design was such that it could be built by local carpenters, lumber suppliers, or farmers. Cost of the materials was \$2.25 per ft^2 of collector area. Figure 1 shows one section of the collector.

Two sections of collector were joined together and used with each of two 18 ft. diameter drying bins. One bin was equipped with a vertical stirring auger powered by a 1½ hp motor to turn the stirring auger and a ¼ hp, 1 rpm motor to move the stirring auger around and across the bin. The other bin had no provision for stirring. Each bin had a perforated false floor.

To avoid shading from the drying bins and a nearby tree the collectors were located approximately 65 ft. from the bins and connected with 18 in. square sheet metal duct with 1 in. of fiberglass insulation fastened to the interior perimeter. Figure 2 shows the layout of the system.

A 1-hp fan was mounted in each duct to pull air through the collector and duct and force it through the grain. A door was installed in the duct ahead of the fan to bypass the collector at night and prevent cooling of the air from back radiation to the sky.

DRYING TEST

Each bin was filled on October 17-18 with approximately 2060 bu. of shelled corn with an average moisture content of 20.8 percent in the stirred bin and 20.4 percent in the unstirred bin. Moisture content of the corn coming from the field was at the desired level for the low temperature solar tests, so the high temperature drying phase was omitted. Continuous operation of the 1-hp fan on each bin was started at 5 p.m. on October 18. Continuous operation of the stirring auger was also started at this time.

Hourly temperatures for the ambient air and for the heated air in the duct for both bins at locations immediately after the collector and ahead and after the fan were recorded throughout the drying period to enable the sensible heat inputs to be calculated. Hourly data for dew point temperature, ambient air temperature, and insolation on a horizontal surface were obtained from the Purdue Agronomy Farm MICROS weather station located 600 ft. east of the drying bins.

Electric meters recorded energy usage of the fans. Power used by the stirring auger was measured periodically with a wattmeter and an average of the readings used to calculate energy usage.

Air flow was determined by measuring the velocity of air exiting the grain through a 25 to 1 reducing cone. The air flow rate in each bin was about 0.9 cfm/bu. While measuring air flow in the stirred bin, the stirring auger was stopped and the grain leveled to reduce any large variations in readings that would have been caused by the grain depth variations.

In order to avoid cooling of the drying air at night by negative radiation from the collector, bypass doors on the ducts were opened manually at 5 p.m. on all but 12 nights during the test and closed at 8 a.m. the following morning. Data from these 12 nights were examined to see the effect of night cooling by the collector.

Samples were collected weekly throughout the depth of corn at two vertical locations in the bin using a vacuum probe. These samples were tested for moisture content and mold infection. Moisture contents were determined by the ASAE standard oven drying method.

TESTS RESULTS

The drying tests were terminated on November 29 after 42 days. Final moisture contents averaged 16.8 percent for the stirred bin and 15.5 percent for the unstirred bin.

Adverse weather conditions prevailed throughout the drying period. Solar radiation was 83 percent of the previous 10-year average and relative humidities were above average.

Table 1 gives a summary of test conditions, energy inputs, and collector performance. The moisture removed during the tests was 16 percent less from the stirred corn than from the unstirred corn. This difference was determined from moisture measurements and confirmed by weight changes during drying.

There was no difference in air flow in the stirred and unstirred corn; however, energy requirements for the same fan producing the same air flow were 12 percent less in the stirred corn. The energy required for the stirring auger was nearly the same as that for the fans; therefore, the electrical energy required for each pound of moisture removed in the stirred bin was nearly twice that in the unstirred bin.

Grain moisture profiles were plotted after each successive two-week drying period (Fig.3). The moisture profiles indicate that stirring the grain was effective in maintaining a uniform moisture content throughout the depth of the bin except for the bottom two feet. After two weeks of drying, the unstirred bin contained grain at 20.2 percent moisture, while the wettest grain in the stirred bin was 19.4 percent moisture. After four weeks of drying, the wettest grain in the unstirred and stirred bins were at 19.0 and 18.1 percent moisture respectively. While these differences in maximum moistures are small, stirring reduced the moisture content of top layers of corn sooner and thereby increased allowable drying time.

The longer holding time at higher moisture contents of the unstirred corn resulted in some increased mold activity. During the third week of drying, seed infected by Aspergillus glaucus increased from below 10 to 20-30 percent and remained at this level throughout the remainder of the test. Infection by Penicillium fungi behaved similarly. In the stirred bin, the percentage of seed infected by these fungi remained below 10 throughout the entire test. Field fungi were present in both bins at about the following levels: Cephalosporium (20%), Fusarium moniliforme (40-50%), and Gibberella zeae (6%). Presence of field fungi are not normally considered a factor in grain quality maintenance in storage.

ASHRAE equations were applied to insolation data obtained from the MICROS weather station to obtain the radiation falling on the tilted flat-plate collector. The collector serving the unstirred bin was shaded more than the collector on the other bin and this may account for its slightly lower efficiency. System efficiency reported in Table 1 considered heat loss from ducts as well as sensible heat from radiation falling on the collector that was lost while they were being bypassed in early morning and late evening.

The hourly average of total sensible heat in the drying air, as measured by temperature rise above dewpoint, is shown in figure 4. Also shown is the relative amount of the total heat supplied by solar energy.

The amount of radiation cooling when the air was pulled through the collector at night was insignificant except on 2 of 12 nights. However, the collector was not bypassed some of the 12 nights because it was cloudy or raining and negative radiation was not expected.

The drop in air temperature in the duct between the collectors and the drying fan ranged from 0 at night to 1.0°F at noon. The average temperature rise from the collectors at noon was about 17°F.

CONCLUSIONS

Solar drying for the low temperature phase of a combination high temperature-low temperature drying system appears feasible with reduced air flow rates. Since the air flow is reduced, continuous stirring of the grain is undesirable; however, with proper management, a stirring auger may be beneficial.

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Peart, R. M. 1977. Stirring of Corn for Solar Heat, In-Bin Drying. Proceedings of the Solar Grain Drying Conference. Urbana-Champaign, Illinois.

Approved as Journal Paper # 7188, Purdue University Agricultural Experiment Station.

Table 1. Summary Table for 1977 Solar Drying Tests

Test Conditions	TEST LOT Stirred	Unstirred
Drying period	Oct. 18-Nov. 29	
Length	42 days	
Lot size, bu.	2061	2064
Initial moisture content, %	20.8	20.4
Final moisture content, %	16.8	15.5
Moisture removed, lb.	5929	7123
Air flow rate, cfm/bu	0.9	0.9
Collector area, ft^2/bu	0.19	0.19
Energy Inputs		
Electrical energy, 10^6 Btu		
Fan	2.91	3.31
Stirring auger	2.61	----
Electrical total	5.52	3.31
Electrical energy utilization Btu/lb moisture removed	952	465
Sensible Heat, 10^6 Btu		
Ambient	14.48	14.64
Solar	8.35	8.08
Fan	2.96	3.16
Total sensible	25.80	25.90
Sensible Heat Utilization		
Btu./lb moisture removed	4350	3640
Sensible Heat, % of Total		
Ambient	56	56
Solar	32	32
Fan	12	12
Collector Performance		
Insolation, 10^6 Btu	16.86	16.86
Collector output, 10^6 Btu	8.35	8.08
Collector efficiency, %	50	48
System efficiency, %	47	45
Max. temperature rise, ^oF	43.8	42.0
Ave. temperature rise (8 am-5 pm) ^oF	11.0	10.6

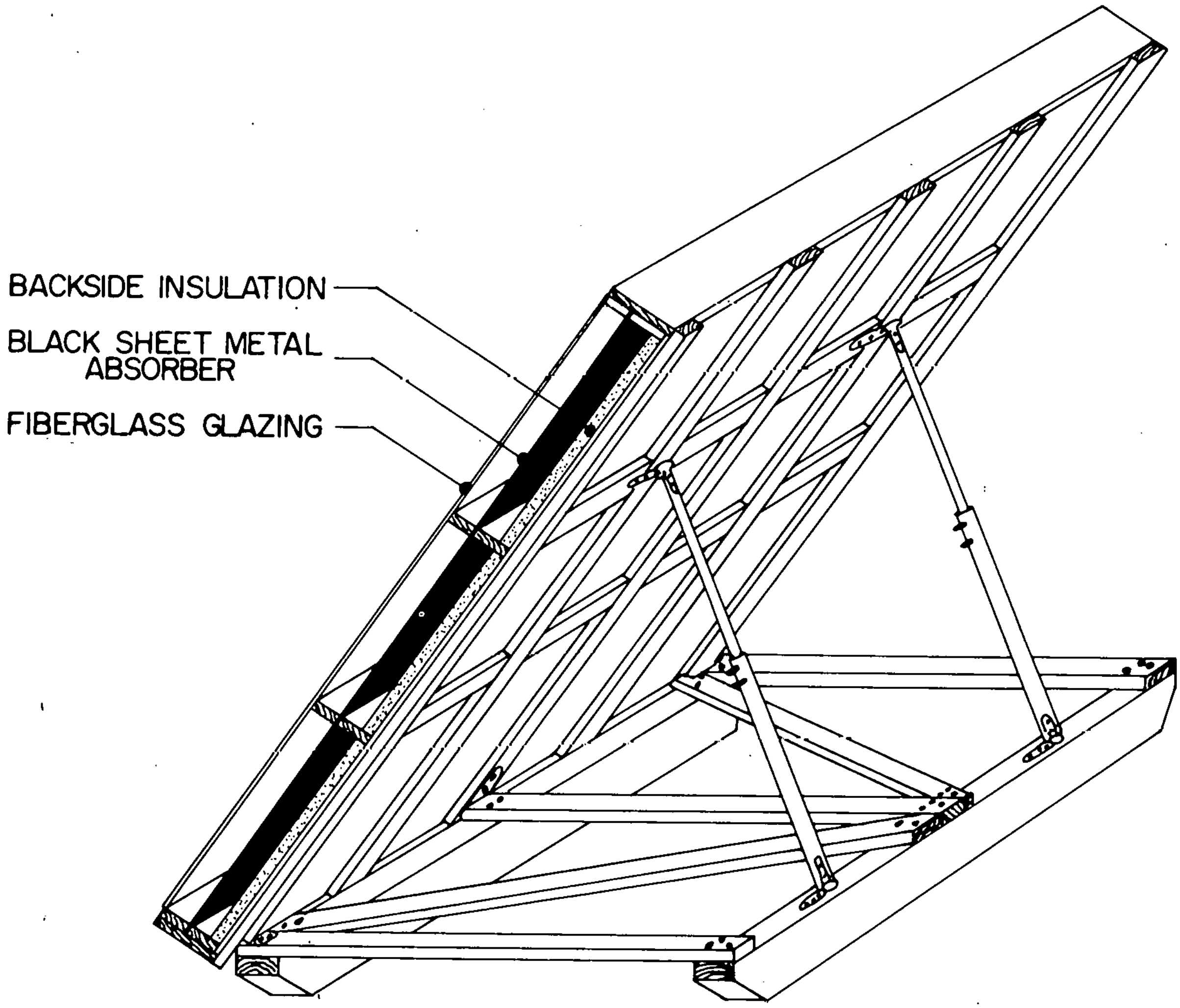


FIGURE 1. A SECTION OF SOLAR COLLECTOR WITH ITS SUPPORTING FRAME

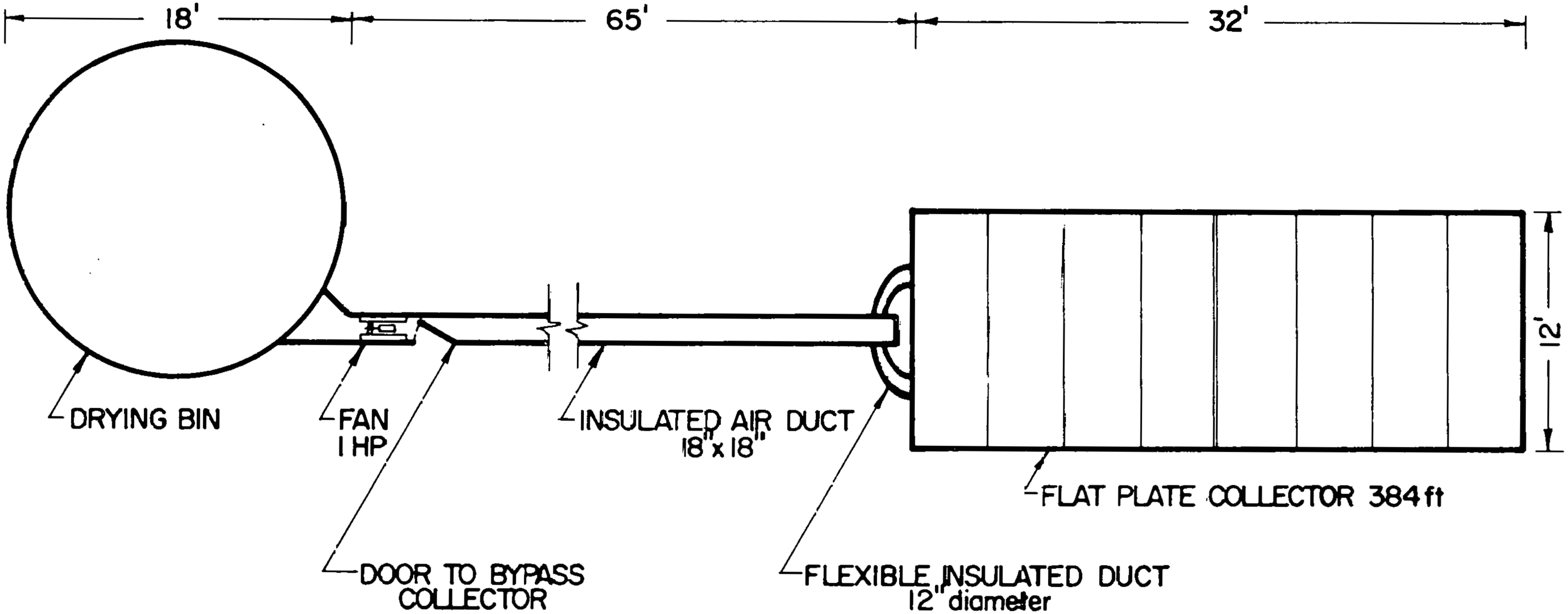
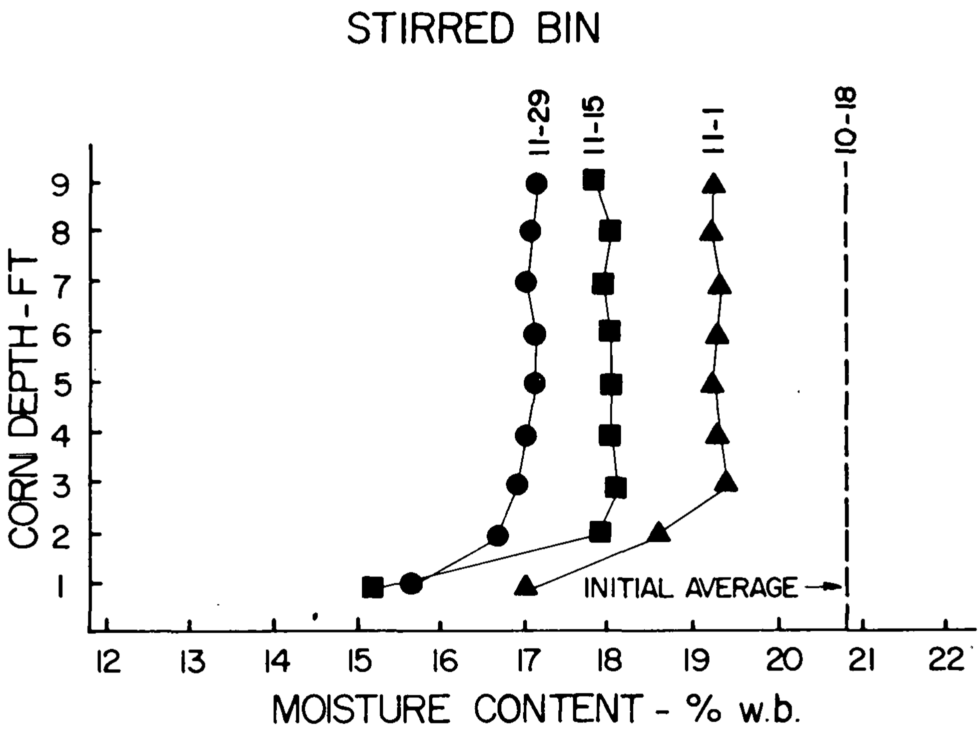


FIGURE 2. LAYOUT OF COLLECTOR, DRYING BIN AND AIR HANDLING SYSTEM FOR SOLAR DRYING TESTS



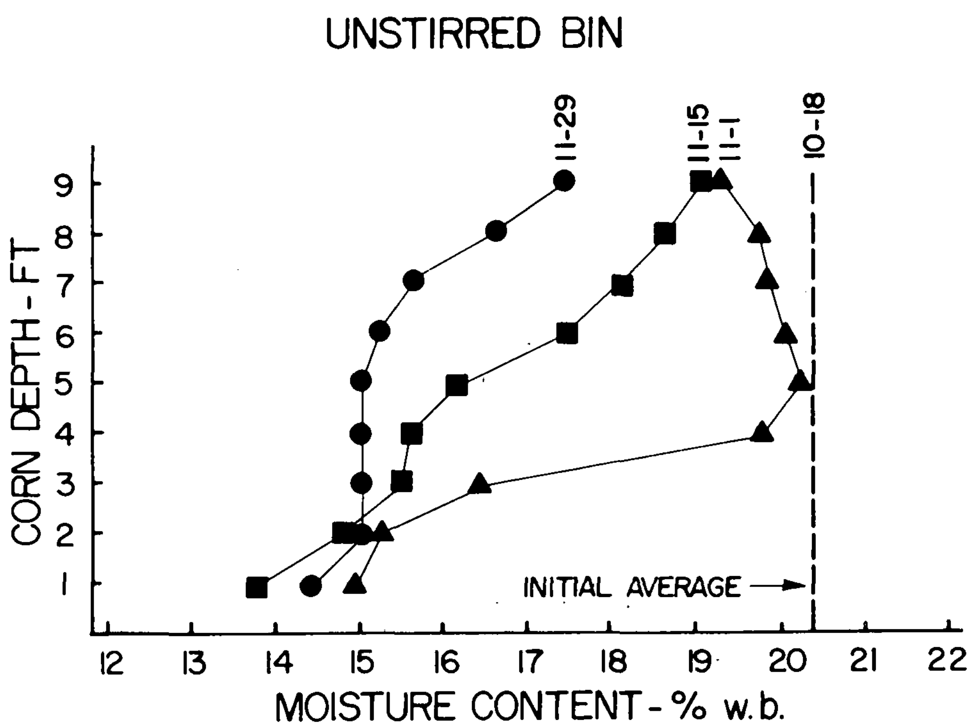


FIGURE 3. GRAIN MOISTURE PROFILES AT THREE DATES DURING THE 1977 SOLAR DRYING TESTS

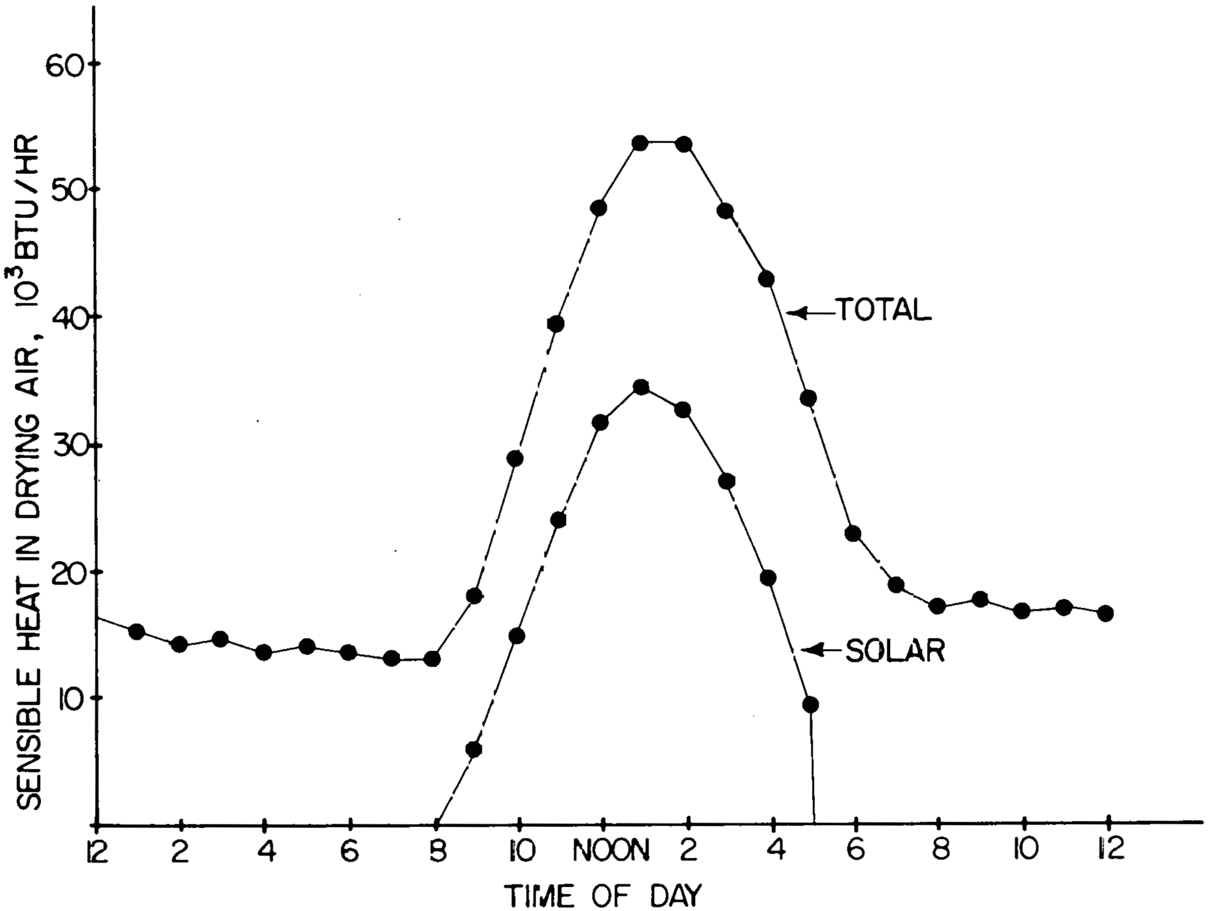


FIGURE 4. HEAT AVAILABLE IN DRYING AIR - AVERAGES FOR 1977 SOLAR DRYING TESTS

SOLAR AND NATURAL AIR GRAIN DRYER PERFORMANCE IN THE CORN PRODUCING AREAS OF THE U.S. - SIMULATION RESULTS

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The application of solar energy to grain drying seems best suited for low temperature systems and most of the solar grain drying research has been done in this area. One major problem in assessing the effect of solar supplementation is the unpredictability of the performance of low temperature drying systems. A thorough understanding of low temperature or natural air drying is necessary to properly evaluate the advantages of using solar energy for grain drying.

A detailed computer simulation study by Pierce and Thompson (1976) evaluated the effect of solar grain drying for the North Central Region of the United States. The drying results presented here represent an expansion of this simulation study to some of the warmer, more humid corn producing areas of the United States and a more detailed evaluation of various management strategies for different climatic regions. This paper is a continuation of the North Central Region study, thus the following is a summarization of that project.

MINIMUM AIRFLOWS

North Central Region Study

A computer simulation model by Thompson (1972) was used to predict drying results for solar supplemented drying systems. Drying results were also predicted for systems using ambient air and several levels of continuous heat. These results served as a basis for comparison when evaluating possible advantages of solar energy in grain drying. Actual radiation and weather data, from one location in each of the twelve North Central region states, were used as inputs to the simulation model.

Airflow rate, initial moisture content, harvest date (with corresponding changes in ambient temperature) and year-to-year weather conditions greatly influence the performance of low heat or natural air grain drying systems (Thompson, 1972). A series of simulation runs were made to illustrate the effect of these factors over the North Central region. The effect of using various levels of continuous heat or solar supplementation for the different locations was also studied. Minimum yearly airflow requirements for each location were determined for selected combinations of the following conditions:

1) Harvest Date (Oct. 1, Oct. 15 and Nov. 1)

2) Initial Moisture Content (20,22, 24 and 26% w.b.)

3) Continuous Heat (Fan & Supplemental - 0, 2, 5 and 8^{o}F temperature rise)

4) Solar Collector Coefficients (Supplemental - 0, 10, 20, 30, 40^{o}F/1000 langleys/day)

Minimum airflow rates were determined for all combinations of harvest date, continuous heat, and solar collector coefficients with an initial moisture content of 24%. The effect of initial moisture content on airflow requirements was determined for an October 15 harvest date, with no continuous or solar heat.

The criteria for determining the minimum airflow requirements for each run was that all the grain in the bin was dried to a moisture content below 15% w.b. with less than one-half percent dry matter decomposition. Continuous fan operation and a full perforated floor were assumed for these minimum airflow rate simulations. In cases where air was pulled over the fan motor, a $2^{o}F$ temperature rise was assumed.

The results from these simulation runs indicated that:

1) Airflow rate is the most important factor in the design and operation of low temperature grain drying systems regardless of whether natural air, continuous supplemental heat or solar supplementation is used. In most cases, if a system is not designed for the proper airflow rate the addition of supplemental heat will only increase the amount of spoilage.

2) Generally, the minimum airflow rate required is not significantly reduced by adding supplemental heat above the approximate $2^{o}F$ temperature rise that can be obtained by pulling the air over the fan motor. The exceptions were central Indiana and Ohio where an additional $3^{o}F$ did reduce the required airflow rate.

3) For a given location, there is almost always 1 or 2 years out of 10 that require a considerably higher airflow rate than the other years especially for higher moisture contents. This increase is caused by unseasonably warmer temperatures during the initial drying period.

4) Across the region, the required airflow rates increased from the cool dry region of North Dakota to the warmer high humidity regions of central Indiana and Ohio.

5) Across the region, the time required for the grain to dry increased from the southern to the northern areas of the region.

New Locations

Four additional states were selected for the minimum airflow studies to represent the other corn producing areas of the U.S. The four states were California, Georgia, Texas and North Carolina. These locations were selected as being representative of the range of conditions under which low temperature corn drying systems might be operated. The specific locations for which temperature and solar radiation were available, the period of record, and the years selected for the study are listed in Table 1. Minimum airflow requirements were determined for the same set of input conditions used in the North Central Region study. Most of the resulting airflow rates were fairly high (2-7 cfm/bu for 24% corn) so a similar set of runs were made using a harvest moisture content of 22%.

Aside from higher airflow requirements, simulation results for these locations indicated trends which were fairly typical of those shown for the North Central Region states. Airflow requirements were highest for North Carolina and Georgia conditions and lowest for Texas (Table 2). Generally, there was no significant advantage to adding supplemental heat for any of these locations as far as reducing airflow requirements were concerned. This was especially true for Texas conditions where humidities were low. For all locations, drying had to be completed quickly to prevent excessive spoilage at the higher temperatures. As a result, drying was usually completed in the fall of the year.

These simulation runs were all made with harvest dates of October 1, October 15, and November 1, for direct comparison with the North Central Region results. Corn harvest in these southern states normally occurs in July and August, thus additional simulations are needed. It is expected that the earlier harvest and resulting higher temperatures will dictate a need for higher airflow rates.

Additional Runs

The relatively high airflow rates required for high moisture contents, early harvest dates and some of the warmer, more humid states indicate that low temperature drying may not be appropriate for all situations. To aid in defining the conditions for which low temperature drying is appropriate and to develop regional airflow recommendations, minimum airflow requirements were determined for all combinations of three harvest dates (Oct. 1, Oct. 15 and Nov. 1) and four moisture contents (20, 22, 24 and 26%). Results from these simulation runs are summarized in Table 2. The airflow rates presented are minimum airflow requirements for the next to worst year (out of 10) studied. A $2^{o}F$ temperature rise from the fan motor was assumed for each set of runs. Runs were also made for Indiana conditions using an additional $3^{o}F$ of supplemental heat and for 4 addi-

Table 1. Summary of data availability and locations selected for Georgia, North Carolina, California and Texas.

	Temperature Data		Radiation Data		
State	Location	Available	Location	Available*	Fall Periods Used
North Carolina	Cape Hatteras	1957-73	Same	1957-74	1963-67, 1969-73
Georgia	Macon	1949-73	Griffin	1953-64	1953-59, 1961-63
California	Fresno	1949-73	Same	1952-74	1961, 1963-66, 1969-73
Texas	Midland	1946-73	Same	1954-74	1954, 1958-59, 1961, 1966-68, 1970-72

*Radiation data is generally not complete for the period indicated.

Table 2. Effect of harvest date and initial moisuture content on the minimum airflow rate (cfm/bu) required to dry corn with less than .5 percent dry matter loss. These airflow rates are for the next to worst year indicated by computer simulation tests using 10 years of actual weather data. A 2 F temperature rise from the fan motor was assumed.

	October 1				October 15				November 1			
	Initial Moisture content				Initial Moisture Content				Initial Moisture Content			
LOCATION	20%	22%	24%	26%	20%	22%	24%	26%	20%	22%	24%	26%
Bismark, North Dakota	.29*	.55*	1.29	2.51	.31*	.43*	.57*	1.30	.36*	.49*	.60*	.88
Huron, South Dakota	.46*	1.30	2.41	4.11	.39*	.61	1.40	3.19	.41*	.55*	.69*	1.05
Lincoln, Nebraska	.93	1.79	3.05	4.25	.43*	1.16	2.07	3.88	.46*	.66*	1.08	2.23
Dodge City, Kansas	.51*	1.12	2.02	3.24	.35*	1.10	2.22	3.97	.33*	.55*	1.03	2.13
St. Cloud, Minnesota	.56*	1.39	3.04	4.28	.45*	.80	1.91	3.13	.42*	.57*	.73*	1.38
Des Moines, Iowa	.82	1.69	2.61	4.48	.58*	1.32	2.18	4.89	.63*	.83	1.08	2.36
Columbia, Missouri	.80	1.74	3.05	5.23	.54*	1.42	2.48	4.78	.43*	.82	1.77	2.78
Madison, Wisconsin	.60*	1.37	3.23	6.00	.48*	1.01	2.24	3.64	.41*	.61*	.92	1.94
Chicago, Illinois	.72*	1.90	3.20	6.16	.55*	1.28	2.70	4.65	.44*	.68*	1.46	2.62
Indianapolis, Indiana	2.35	2.89	5.61	9.51	1.16	2.07	4.10	5.40	.95	1.90	3.52	4.81
Indianapolis, Indiana**	.91	2.63	4.56	7.41	.53*	1.11	1.87	3.15	.45*	.80	1.66	2.85
Lansing, Michigan	1.00	1.81	2.98	5.70	.75	1.79	2.75	3.89	.54*	.96	1.75	3.07
Mansfield, Ohio	.82	1.86	3.24	4.95	.60*	1.23	2.55	6.07	.45*	.81	1.66	2.99
Midland, Texas	.92	2.01	3.55	6.05	.64*	1.30	2.76	4.59	.34*	.82	1.70	2.81
Fresno, California	.77	1.45	2.74	4.39	1.24	2.09	3.60	5.27	1.08	2.71	4.76	5.86
Macon, Georgia	1.45	3.84	6.62	12.37	1.02	2.59	4.42	7.15	.73*	1.65	2.62	6.08
Cape Hatteras, No. Carolina	1.90	4.28	9.31	16.09	1.71	3.80	6.26	14.83	1.64	2.40	4.56	7.76
Sioux city, Nebraska	.58*	1.40	2.52	3.71	.57*	1.03	1.96	3.64	.49*	.65*	.93	1.43
Grand Island, Nebraska	.35*	.92	2.08	3.19	.32*	.74*	1.54	3.14	.34*	.49*	.83	1.30
North Platte, Nebraska	.29*	.67*	1.27	2.35	.27*	.40*	1.00	1.72	.31*	.46*	.57*	1.00
Scottsbluff, Nebraska	.21*	.43*	.95	1.73	.22*	.35*	.64*	1.31	.24*	.36*	.57*	.87

* Airflow rates below .75 cfm/bu are considered aeration not drying. Rates larger than 0.75 cfm/bu are recommended for drying

** 3 F continuous heat (in addition to the 2 F from the fan) was assumed for these simulation runs.

tional Nebraska locations.

Now that minimum airflow requirements are available for a wide range of conditions, the next step was to determine how these results can best be used in designing and operating low temperature grain drying systems.

MANAGEMENT STUDIES

The North Central region study included a preliminary management study for specific bin situations operated under Des Moines, Iowa conditions. Various fan and heat supplementation strategies for low temperature bin systems filled with a single loading were studied.

In initial attempts at studying the effect of various management strategies, a single design airflow rate was selected for a particular location and moisture content. Specifically, this was the airflow which allowed for successful drying 9 years out of 10 assuming an October 15 harvest date and a 2°F temperature rise from the fan motor. One of the problems associated with this approach was that the design airflow rate was insufficient as much as one half the time for harvest dates earlier than October 15. Another problem was deciding on a moisture content for which the system should be designed.

The results from the fan management study indicated that fan energy requirements could be reduced by operating the fan intermittently over a "winter holding period" when drying potential is low. Under Iowa conditions, the minimum airflows (based upon continuous fan operation) were found to be adequate for use with intermittent fan operation.

The supplemental heat management study compared results for systems operated with natural air, two levels of continuous heat and one level of solar supplementation. It is difficult to directly compare the drying results for the different levels of heat supplementation because of differences in drying times, final average moisture content and spoilage levels. Comparisons are also complicated due to considerable variations in year to-year weather conditions. To enable direct comparisons of different managements, each system performance factor was assigned an economic value. Total drying costs included fixed costs for equipment, energy costs for the fan and heaters, cost of a solar collector and penalty costs for overdrying (below 15.5%) and spoilage of the grain. These systems were then evaluated on the basis of a "drying cost". Generally, results from this preliminary study indicated:

1) Drying time was more predictable by adding some supplemental heat.

2) Energy requirements were generally lowest for solar supplemented systems and highest for systems using continuous heat.

3) Overdrying was more of a problem when supplemental heat was added.

4) Percent dry matter decomposition generally was decreased by adding supplemental heat or harvesting at lower moisture contents.

5) Overall drying costs were highest with the solar supplemented systems.

Fan Operation

Minnesota, Iowa, Indiana, Missouri, Georgia and Texas were selected for system management studies. A procedure similar to the one developed for the Iowa management studies was used to determine appropriate fan operating schedules. Tables of equilibrium relative humidity and temperature were used to define "winter holding periods". General fan operation was to run the fan continuously until the start of the holding period, two hours/day during the holding period and then continuous until the grain was dry. The dates indicating the winter holding period for each of the six locations are shown in Table 3. If continuous heat supplementation was used, the heater was operated only during the initial period of continuous fan operation. The solar collector was assumed to be in operation over the entire drying season.

The simulation results indicated two changes needed in the management strategy presented above. First, spoilage problems were noted if the drying front had not moved completely

Table 3. Dates selected to indicate periods where intermittent fan operation is desirable.

	Fall Shutdown	Spring Startup
Indiana	November 25	March 10
Missouri	December 16	March 3
Iowa	December 2	March 7
Minnesota	November 18	April 7
Georgia	continuous fan operation	
Texas	continuous fan operation	

through the bin before the winter holding period. Therefore, continuous fan operation was continued until the moisture content of the top layer of grain was below 18%. Typically, this did not extend the period of continuous fan operation more than a few weeks into the holding period. Secondly, continuous fan operation was not resumed in the spring until the first day the average temperature was greater than 45^{o}F after the end of the holding period.

Heat Supplementation

Simulation runs were made for the airflow rates shown in Table 2 using the fan operating schedules described in the preceding section. Four levels of heat supplementation were compared in these runs: 2^{o}F (from the fan motor), 2 + 3^{o}F and 2 + 6^{o}F of continuous heat and 2^{o}F+ solar supplementation. Output available from these runs includes average final moisture content, percent dry matter decomposition, and hours of fan and heater operation. The minimum, average and maximum values for these outputs (ten years) are presented in Table 4.

For several of the situations studied, percent dry matter decomposition exceeded .5 for two or more years. This indicates that either the airflow requirements predicted for continuous fan operation (Table 2) are too low or that higher airflow rates are required when using intermittent fan operation. Since this problem also existed for the Texas and Georgia management runs (continuous airflow), at least part of the problem lies with the procedure for determining minimum airflow requirements. For Indianapolis conditions, it appears that supplemental heat should be added at least until the drying zone has moved completely through the bin. Other possible problem areas associated with management techniques are being studied.

Economic Evaluation

The results from the management studies (summarized in Table 4) were analyzed using an economic evaluation approach similar to that used for the Iowa study. However, the objectives of this study were somewhat different than those of the Iowa study. Rather than trying to design a low temperature system for each of the locations, more emphasis was placed upon determining the relative merits of adding supplemental heat. This change in objectives resulted in two major differences between the studies. First, there was no attempt to select an airflow rate to represent a range of harvest dates. Simulation runs were made at the minimum airflow rate required for each harvest date and initial moisture content. The second difference was that fixed costs for equipment were not included as a part of the drying cost. The cost of a solar collector was still considered. As a result, caution should be exercised when making comparisons between operating costs for different harvest dates, moisture contents or locations.

The magnitude of the operating costs are very situation specific and depend on bin diameter, depth and fan, heater or collector sizes. They will also vary with the different cost values assigned to each factor. A computer program 'DRYCOST' was developed to generate drying costs for the various situations. A sample output from this program is shown in Table 5.

The results from the management studies were analyzed for a standard set of cost values and a specific bin situation. The study dealt with a 24 foot diameter bin holding 6000 bushels (16.6 ft deep). Knowing the bin specifications, the required airflow rate and the desired temperature rise, the fan size and heater or collector sizes were calculated. An efficiency of 50% was assumed when calculating collector size. The collector cost was based upon a purchase price of \$1.50/ft^2, economic life of 3 years and an interest rate of 11%. A corn price of \$2/bu and electrical costs of \$0.035/kW-hr were also assumed for the study.

The operating costs resulting from the economic study are presented in Table 6. Notice that operating costs were not calculated for situations where airflow rates higher than 2 cfm/bu are required. This airflow level was arbitrarily selected as the point above which single fill low temperature systems do not appear to be economically feasible. This implies that the greatest application for full bin drying will be for relatively low moisture content grain (22%) and for later harvest dates.

Table 4. Predicted drying results for the 6 locations included in the management study. The drying tests were simulated using 10 years of actual weather data.

MACON, GEORGIA (10 YEARS)

10/ 1 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
18%	0.75	2F	11.5	12.5	14.0	.173	.282	.479	696	914	1200	0	0	0
		2+3F	10.4	11.7	13.4	.166	.273	.441	696	763	864	696	763	864
		2+6F	9.6	10.8	12.5	.171	.272	.429	696	696	696	696	696	696
		2+SC	10.2	11.4	13.5	.165	.271	.438	696	746	864	0	0	0
20%	1.45	2F	10.6	12.5	14.2	.227	.421	.784	528	628	1032	0	0	0
		2+3F	10.5	11.8	14.0	.221	.382	.656	360	511	528	360	511	528
		2+6F	9.7	10.9	12.9	.217	.365	.608	360	511	528	360	511	528
		2+SC	10.0	11.6	14.1	.221	.375	.625	360	511	528	0	0	0
22%	3.84	2F	10.5	12.2	13.5	.166	.343	.511	192	410	864	0	0	0
		2+3F	9.7	11.6	13.6	.166	.302	.489	192	292	360	192	292	360
		2+6F	9.0	10.7	12.5	.163	.274	.397	192	242	360	192	242	360
		2+SC	9.4	11.1	12.3	.158	.305	.506	192	360	864	0	0	0
24%	6.62	2F	10.6	12.1	13.0	.197	.376	.588	192	326	864	0	0	0
		2+3F	10.9	11.9	13.8	.192	.315	.488	192	208	360	192	208	360
		2+6F	10.1	11.0	12.7	.191	.273	.355	192	192	192	192	192	192
		2+SC	9.6	11.1	13.8	.187	.320	.490	192	292	864	0	0	0

10/15 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
18%	0.75	2F	12.2	12.8	13.7	.095	.179	.275	864	964	1200	0	0	0
		2+3F	11.2	11.8	12.4	.094	.175	.273	696	796	1032	696	796	1032
		2+6F	10.2	10.8	11.8	.097	.172	.266	696	712	864	696	712	864
		2+SC	10.9	11.6	12.5	.095	.174	.268	696	780	1032	0	0	0
20%	1.02	2F	11.8	12.5	13.5	.165	.346	.612	696	813	1032	0	0	0
		2+3F	10.8	11.4	12.2	.175	.335	.575	696	729	864	696	729	864
		2+6F	10.1	10.7	11.9	.180	.330	.541	528	662	696	528	662	696
		2+SC	10.7	11.4	12.3	.176	.331	.566	528	712	864	0	0	0
22%	2.59	2F	11.2	12.3	14.0	.114	.302	.505	360	444	696	0	0	0
		2+3F	10.2	11.2	13.2	.112	.278	.423	360	376	528	360	376	528
		2+6F	9.4	10.4	12.1	.112	.265	.389	360	360	360	360	360	360
		2+SC	10.0	11.0	13.4	.112	.278	.441	360	376	528	0	0	0
24%	4.42	2F	10.9	12.0	14.2	.121	.333	.597	192	360	528	0	0	0
		2+3F	9.8	11.1	12.9	.123	.300	.541	192	326	528	192	326	528
		2+6F	8.9	11.0	12.0	.124	.271	.442	192	225	360	192	225	360
		2+SC	9.3	11.1	13.1	.120	.292	.549	192	309	528	0	0	0

11/ 1 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
18%	0.75	2F	12.4	13.3	14.0	.113	.145	.207	864	998	1200	0	0	0
		2+3F	11.3	12.3	13.0	.114	.157	.273	696	847	864	696	847	864
		2+6F	10.4	11.6	12.9	.114	.157	.266	696	712	864	696	712	864
		2+SC	11.5	12.4	13.3	.114	.143	.200	696	847	864	0	0	0
20%	0.75	2F	12.6	13.4	14.1	.275	.369	.539	1032	1284	1536	0	0	0
		2+3F	11.7	12.4	13.1	.278	.360	.509	864	1015	1032	864	1015	1032
		2+6F	10.5	11.4	12.2	.284	.364	.517	864	931	1032	864	931	1032
		2+SC	11.7	12.5	13.3	.274	.357	.513	1032	1048	1200	0	0	0
22%	1.66	2F	11.7	13.1	14.0	.255	.372	.606	528	712	864	0	0	0
		2+3F	10.6	12.2	13.3	.232	.338	.571	528	528	528	528	528	528
		2+6F	9.6	11.2	12.2	.202	.308	.514	528	528	528	528	528	528
		2+SC	10.6	12.3	13.6	.230	.331	.554	528	528	528	0	0	0
24%	2.62	2F	11.0	12.9	14.3	.216	.383	.677	528	561	696	0	0	0
		2+3F	11.6	12.4	12.9	.180	.336	.570	360	444	528	360	444	528
		2+6F	10.2	11.2	12.3	.173	.328	.559	360	360	360	360	360	360
		2+SC	10.0	12.4	14.1	.183	.332	.568	360	477	528	0	0	0

TABLE 4. (CONTINUED)

DES MOINES, IOWA (10 YEARS)

10/ 1 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
20%	0.82	2F	11.9	13.5	14.5	.221	.335	.494	864	1528	2746	0	0	0
		2+3F	11.9	12.6	13.5	.227	.317	.478	696	998	1200	696	998	1200
		2+6F	10.9	11.6	12.1	.228	.321	.499	696	864	1032	696	864	1032
		2+SC	11.9	13.0	13.8	.237	.315	.470	696	1015	1368	0	0	0
22%	1.69	2F	12.0	13.5	14.6	.227	.368	.735	528	712	1032	0	0	0
		2+3F	11.0	12.3	12.8	.222	.358	.684	528	595	696	528	595	696
		2+6F	9.9	11.1	12.0	.213	.353	.722	360	528	696	360	528	696
		2+SC	10.9	12.2	13.1	.219	.359	.737	360	561	696	0	0	0
24%	2.61	2F	11.3	13.1	14.1	.225	.485	****	360	544	696	0	0	0
		2+3F	10.3	11.9	13.0	.235	.447	****	360	460	528	360	460	528
		2+6F	9.8	11.5	12.7	.222	.399	.807	360	376	528	360	376	528
		2+SC	10.2	12.0	12.9	.232	.449	****	360	460	528	0	0	0
26%	4.48	2F	11.1	13.1	14.4	.239	.443	****	360	444	528	0	0	0
		2+3F	10.3	12.5	13.8	.229	.389	.727	192	360	528	192	360	528
		2+6F	9.4	11.5	12.7	.236	.365	.589	192	343	360	192	343	360
		2+SC	10.0	12.6	13.9	.236	.395	.822	192	360	528	0	0	0

10/15 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
20%	0.75	2F	12.1	12.9	14.1	.156	.282	.463	1256	2067	2732	0	120	1200
		2+3F	12.0	13.0	13.6	.140	.236	.399	1032	1435	2410	1032	1183	1200
		2+6F	11.2	12.3	13.7	.146	.231	.411	1032	1082	1200	1032	1082	1200
		2+SC	11.1	13.0	14.6	.146	.245	.398	1200	1623	2358	0	0	0
22%	1.32	2F	12.2	13.4	14.5	.168	.332	.612	864	1363	2250	0	0	0
		2+3F	12.2	13.1	14.0	.168	.302	.624	696	813	1032	696	813	1032
		2+6F	11.1	11.9	12.7	.178	.305	.628	696	696	696	696	696	696
		2+SC	11.2	13.2	14.3	.168	.304	.613	696	1035	2074	0	0	0
24%	2.18	2F	12.4	13.6	14.2	.201	.409	.883	528	1213	2082	0	0	0
		2+3F	11.4	12.7	13.7	.204	.375	.915	528	561	696	528	561	696
		2+6F	10.4	11.7	12.5	.206	.376	.954	528	528	528	528	528	528
		2+SC	11.5	13.2	14.4	.199	.373	.908	528	578	696	0	0	0
26%	4.89	2F	12.0	13.1	13.9	.164	.360	.986	360	736	1906	0	0	0
		2+3F	10.9	12.3	13.4	.152	.312	.783	360	360	360	360	360	360
		2+6F	10.1	11.3	12.3	.147	.300	.642	360	360	360	360	360	360
		2+SC	10.9	12.6	13.9	.151	.317	.829	360	376	528	0	0	0

11/ 1 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
20%	0.75	2F	12.1	12.8	14.5	.153	.255	.502	2164	2861	4002	0	0	0
		2+3F	12.0	12.9	14.5	.138	.212	.405	1578	2371	2924	864	864	864
		2+6F	12.1	13.2	14.2	.142	.190	.361	1242	1902	2602	864	864	864
		2+SC	11.1	12.2	14.2	.133	.203	.371	1484	2294	2896	0	0	0
22%	0.83	2F	12.0	12.8	14.5	.250	.409	.880	2626	3134	4450	0	0	0
		2+3F	11.8	12.8	14.4	.220	.354	.721	2164	2749	3372	864	864	864
		2+6F	12.0	13.0	14.4	.231	.328	.619	1578	2287	2910	864	864	864
		2+SC	10.8	11.9	13.8	.227	.329	.613	2054	2590	3358	0	0	0
24%	1.08	2F	11.3	12.6	14.5	.297	.521	****	2222	2863	4282	0	0	0
		2+3F	11.1	12.8	14.5	.315	.485	****	1900	2460	2896	864	864	864
		2+6F	11.1	12.9	14.5	.327	.471	.965	1498	2143	2588	864	864	864
		2+SC	9.8	11.7	14.5	.320	.461	.868	1638	2318	3036	0	0	0
26%	2.36	2F	10.6	12.9	14.5	.282	.415	.948	864	1481	1944	0	0	0
		2+3F	11.6	13.0	13.9	.239	.376	.927	696	912	1752	696	763	864
		2+6F	10.7	12.2	13.9	.245	.366	.873	528	696	864	528	696	864
		2+SC	9.9	12.6	14.1	.260	.382	.871	696	1109	1752	0	0	0

TABLE 4. (CONTINUED)

INDIANAPOLIS, INDIANA (10 YEARS)

10/ 1 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
20%	2.35	2F	12.1	13.3	14.6	.079	.182	.484	360	700	2250	0	0	0
	0.91	2+3F	11.4	13.1	14.2	.172	.343	.550	696	1112	2504	696	998	1368
		2+6F	10.2	12.0	13.3	.177	.335	.557	696	847	864	696	847	864
		2+SC	11.4	12.9	14.3	.173	.353	.646	696	1344	2418	0	0	0
22%	2.89	2F	11.9	13.1	14.6	.127	.316	.896	360	700	2250	0	0	0
	2.63	2+3F	10.9	12.5	13.9	.130	.281	.558	360	444	528	360	444	528
		2+6F	10.0	11.9	13.1	.126	.262	.467	360	360	360	360	360	360
		2+SC	10.7	12.5	14.1	.130	.283	.567	360	444	528	0	0	0
24%	5.61	2F	11.9	13.3	14.5	.126	.320	.970	192	616	2250	0	0	0
	4.56	2+3F	11.5	13.2	14.4	.142	.294	.524	192	343	360	192	343	360
		2+6F	10.6	12.1	13.2	.138	.271	.495	192	326	360	192	326	360
		2+SC	11.7	13.0	14.0	.141	.293	.534	192	376	528	0	0	0
26%	9.51	2F	11.9	13.4	14.5	.113	.286	.663	192	410	1032	0	0	0
	7.41	2+3F	12.0	13.2	14.4	.143	.308	.620	192	208	360	192	208	360
		2+6F	11.0	12.0	13.1	.135	.274	.570	192	192	192	192	192	192
		2+SC	11.8	13.0	14.6	.137	.311	.694	192	276	528	0	0	0

10/15 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
20%	1.16	2F	11.8	13.3	14.3	.142	.263	.411	696	2085	3236	0	0	0
	0.75	2+3F	12.1	13.2	14.5	.177	.346	.572	1032	2141	3726	1032	1032	1032
		2+6F	10.9	12.7	13.8	.170	.269	.354	864	1377	2418	864	1015	1032
		2+SC	10.9	12.7	14.0	.203	.316	.409	1032	2010	2718	0	0	0
22%	2.07	2F	12.1	13.2	14.6	.115	.283	.429	528	1611	3068	0	0	0
	1.11	2+3F	11.6	13.2	14.5	.215	.394	.549	864	1456	2374	864	981	1032
		2+6F	10.9	12.6	13.8	.219	.353	.438	696	1019	2250	696	897	1032
		2+SC	11.3	12.5	13.9	.212	.410	.516	864	1644	2396	0	0	0
24%	4.10	2F	10.9	12.8	14.4	.109	.283	.460	360	1221	3068	0	0	0
	1.87	2+3F	11.6	13.2	14.5	.239	.423	.534	528	1016	2250	528	813	1032
		2+6F	10.4	12.3	13.5	.230	.396	.508	528	612	696	528	612	696
		2+SC	11.4	12.9	14.6	.234	.438	.626	528	1113	1746	0	0	0
26%	5.40	2F	10.6	12.7	14.1	.134	.374	.559	192	1281	3068	0	0	0
	3.15	2+3F	11.3	13.2	14.8	.225	.413	.569	360	658	1664	360	595	1032
		2+6F	9.6	12.5	14.2	.226	.395	.542	360	444	528	360	444	528
		2+SC	11.5	13.2	14.6	.225	.438	.566	360	866	1578	0	0	0

11/ 1 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
20%	0.95	2F	12.4	13.3	14.3	.218	.358	.474	1724	2737	4040	0	0	0
	0.75	2+3F	12.4	13.5	14.4	.250	.388	.577	2046	2794	3574	696	696	696
		2+6F	12.4	13.4	14.4	.255	.328	.475	1388	2544	3420	696	696	696
		2+SC	11.0	12.5	14.1	.196	.334	.423	1652	2534	3130	0	0	0
22%	1.90	2F	12.5	13.4	14.3	.177	.295	.374	528	1676	2454	0	0	0
	0.80	2+3F	12.4	13.4	14.4	.446	.707	.919	2200	3164	3882	696	696	696
		2+6F	12.3	13.4	14.4	.422	.595	.792	2046	2887	3728	696	696	696
		2+SC	10.9	12.3	13.1	.380	.571	.677	1864	2979	3872	0	0	0
24%	3.52	2F	12.0	13.3	14.4	.189	.304	.393	360	1401	2454	0	0	0
	1.66	2+3F	11.9	13.1	14.4	.339	.487	.650	696	1886	2776	696	696	696
		2+6F	10.9	12.9	14.4	.302	.420	.619	696	1292	1782	696	696	696
		2+SC	10.8	12.4	13.7	.311	.473	.652	696	1679	2258	0	0	0
26%	4.81	2F	11.2	12.8	14.4	.151	.363	.482	360	1302	2454	0	0	0
	2.85	2+3F	12.0	13.1	14.6	.258	.446	.736	528	1209	1870	528	662	696
		2+6F	11.1	12.9	14.3	.252	.376	.560	360	578	696	360	578	696
		2+SC	10.6	12.6	14.0	.307	.500	.713	528	1213	1446	0	0	0

TABLE 4. (CONTINUED)

ST. CLOUD, MINNESOTA (10 YEARS)

10/ 1 HARVEST DATE

M.C.	CFM/BU		FINAL MOISTURE MIN	AVE	MAX	% DM DECOMP MIN	AVE	MAX	FAN HOURS MIN	AVE	MAX	HEATER HOURS MIN	AVE	MAX
20%	0.75	2F	11.5	12.8	13.9	.195	.291	.383	1256	2224	2730	0	0	0
		2+3F	12.6	13.4	14.1	.172	.256	.401	1032	1385	1918	1032	1166	1200
		2+6F	11.6	12.4	13.2	.181	.253	.419	864	1082	1200	864	1082	1200
		2+SC	10.8	12.7	13.9	.171	.264	.389	1032	1732	2210	0	0	0
22%	1.39	2F	11.8	13.0	14.7	.229	.345	.542	696	1458	2210	0	0	0
		2+3F	11.9	12.9	14.5	.217	.316	.474	696	813	1032	696	813	1032
		2+6F	10.9	11.9	13.1	.217	.315	.453	528	679	864	528	679	864
		2+SC	10.9	12.8	14.0	.216	.315	.456	696	933	1728	0	0	0
24%	3.04	2F	10.8	13.0	14.5	.187	.305	.535	360	787	1750	0	0	0
		2+3F	11.3	12.5	14.1	.172	.267	.469	360	477	528	360	477	528
		2+6F	10.7	11.9	13.0	.163	.249	.395	360	376	528	360	376	528
		2+SC	9.6	12.2	14.1	.172	.277	.500	360	640	1728	0	0	0
26%	4.28	2F	11.0	13.1	14.5	.210	.370	.736	360	681	1728	0	0	0
		2+3F	11.4	12.9	14.1	.196	.316	.526	360	376	528	360	376	528
		2+6F	10.5	11.8	12.8	.200	.307	.475	360	360	360	360	360	360
		2+SC	11.0	12.5	14.2	.197	.337	.556	360	547	1560	0	0	0

10/15 HARVEST DATE

M.C.	CFM/BU		FINAL MOISTURE MIN	AVE	MAX	% DM DECOMP MIN	AVE	MAX	FAN HOURS MIN	AVE	MAX	HEATER HOURS MIN	AVE	MAX
20%	0.75	2F	11.6	12.5	13.6	.138	.247	.323	2256	2618	2974	0	0	0
		2+3F	11.4	12.8	13.7	.123	.212	.293	1598	2188	2548	864	864	864
		2+6F	12.6	13.4	14.0	.122	.197	.294	1298	1702	2226	864	864	864
		2+SC	10.4	12.1	14.2	.128	.212	.295	1598	2065	2498	0	0	0
22%	0.80	2F	11.5	12.5	13.7	.233	.419	.627	2564	3142	3780	0	0	0
		2+3F	11.3	12.6	13.6	.222	.387	.610	2088	2566	2856	864	864	864
		2+6F	12.2	13.1	14.1	.225	.373	.585	1598	2083	2504	864	864	864
		2+SC	10.2	11.5	13.1	.218	.382	.581	2044	2537	2996	0	0	0
24%	1.91	2F	10.8	12.5	14.1	.174	.370	.624	864	1477	1750	0	0	0
		2+3F	11.4	13.1	14.3	.176	.338	.667	696	924	1582	696	796	864
		2+6F	11.0	12.3	13.5	.184	.328	.666	528	662	864	528	662	864
		2+SC	9.8	12.1	14.4	.174	.355	.654	696	1253	1546	0	0	0
26%	3.13	2F	10.8	12.8	14.2	.195	.420	.839	528	1163	1538	0	0	0
		2+3F	11.6	13.1	14.6	.197	.383	.914	528	713	1538	528	645	864
		2+6F	10.7	12.0	13.5	.195	.382	.956	360	494	528	360	494	528
		2+SC	9.6	12.4	14.1	.197	.398	.901	528	900	1414	0	0	0

11/ 1 HARVEST DATE

M.C.	CFM/BU		FINAL MOISTURE MIN	AVE	MAX	% DM DECOMP MIN	AVE	MAX	FAN HOURS MIN	AVE	MAX	HEATER HOURS MIN	AVE	MAX
20%	0.75	2F	11.0	12.3	13.2	.154	.217	.290	3034	3632	4852	0	0	0
		2+3F	11.0	12.4	13.3	.145	.197	.289	2572	3031	3788	528	528	528
		2+6F	11.6	12.6	13.6	.122	.171	.243	2250	2606	3158	528	528	528
		2+SC	10.6	11.4	12.9	.139	.183	.230	2404	2963	3914	0	0	0
22%	0.75	2F	10.9	12.3	13.1	.238	.326	.455	3790	4347	4852	0	0	0
		2+3F	11.0	12.3	13.1	.232	.318	.425	3342	3937	4852	528	528	528
		2+6F	11.0	12.3	13.2	.218	.307	.435	3048	3493	4082	528	528	528
		2+SC	10.4	11.4	12.7	.232	.279	.324	3174	3682	4516	0	0	0
24%	0.75	2F	11.7	12.7	13.7	.346	.518	.884	4070	4531	4852	0	0	0
		2+3F	10.9	12.5	13.3	.367	.465	.551	3944	4451	4852	528	528	528
		2+6F	11.0	12.2	13.1	.371	.504	.695	3804	4212	4852	528	528	528
		2+SC	10.8	11.8	13.4	.346	.442	.557	3754	4023	4516	0	0	0
26%	1.38	2F	11.0	12.3	13.9	.359	.481	.597	2698	3262	4362	0	0	0
		2+3F	11.0	12.4	13.9	.354	.470	.614	2390	2845	4362	528	528	528
		2+6F	11.0	12.3	13.9	.336	.463	.675	2082	2385	282[illegible]	528	528	528
		2+SC	10.3	11.4	12.5	.348	.448	.554	2376	2694	3578	0	0	0

TABLE 4. (CONTINUED)

COLUMBIA, MISSOURI (10 YEARS)

10/ 1 HARVEST DATE

M.C.	CFM/BU		FINAL MOISTURE MIN	AVE	MAX	% DM DECOMP MIN	AVE	MAX	FAN HOURS MIN	AVE	MAX	HEATER HOURS MIN	AVE	MAX
20%	0.80	2F	10.9	12.8	14.6	.222	.377	.601	696	1270	3084	0	0	0
		2+3F	9.9	11.8	13.4	.220	.371	.644	696	914	1032	696	914	1032
		2+6F	9.2	10.9	12.4	.215	.374	.655	696	830	864	696	830	864
		2+SC	9.9	11.9	13.7	.218	.367	.622	696	897	1032	0	0	0
22%	1.74	2F	9.8	12.4	13.9	.193	.419	.953	360	595	696	0	0	0
		2+3F	8.9	11.4	13.1	.186	.400	.883	360	511	528	360	511	528
		2+6F	8.2	10.5	11.9	.186	.382	.852	360	494	528	360	494	528
		2+SC	8.7	11.4	13.2	.188	.397	.888	360	511	528	0	0	0
24%	3.05	2F	9.3	12.4	14.3	.178	.451	****	360	477	528	0	0	0
		2+3F	8.7	11.9	13.4	.190	.387	.887	360	360	360	360	360	360
		2+6F	9.3	11.1	12.2	.196	.370	.864	192	343	360	192	343	360
		2+SC	8.5	11.9	13.5	.190	.381	.887	360	360	360	0	0	0
26%	5.23	2F	9.5	12.9	14.6	.198	.387	.905	192	393	528	0	0	0
		2+3F	8.8	12.0	13.7	.201	.344	.686	192	292	360	192	292	360
		2+6F	8.2	10.6	12.5	.201	.313	.571	192	208	360	192	208	360
		2+SC	8.6	11.8	14.2	.200	.338	.694	192	276	528	0	0	0

10/15 HARVEST DATE

M.C.	CFM/BU		FINAL MOISTURE MIN	AVE	MAX	% DM DECOMP MIN	AVE	MAX	FAN HOURS MIN	AVE	MAX	HEATER HOURS MIN	AVE	MAX
20%	0.75	2F	12.0	13.3	14.3	.205	.282	.374	864	1652	3012	0	0	0
		2+3F	11.3	12.5	13.9	.191	.271	.390	864	1082	1368	864	1082	1368
		2+6F	10.7	11.6	12.9	.187	.274	.401	696	948	1200	696	948	1200
		2+SC	11.6	12.9	14.4	.190	.267	.387	864	1146	1836	0	0	0
22%	1.42	2F	11.8	13.2	14.3	.181	.326	.516	528	1018	2412	0	0	0
		2+3F	10.7	12.3	13.3	.169	.316	.532	528	696	864	528	696	864
		2+6F	9.8	11.2	12.5	.176	.318	.544	528	612	696	528	612	696
		2+SC	10.8	12.5	13.8	.171	.313	.520	528	712	1032	0	0	0
24%	2.48	2F	11.4	12.9	14.6	.189	.367	.679	360	750	2076	0	0	0
		2+3F	10.4	12.0	14.2	.188	.339	.607	360	477	528	360	477	528
		2+6F	9.6	11.0	13.0	.180	.334	.581	360	427	528	360	427	528
		2+SC	10.4	12.2	13.9	.190	.341	.611	360	494	696	0	0	0
26%	4.78	2F	10.5	12.5	14.5	.162	.330	.541	360	427	864	0	0	0
		2+3F	9.8	11.2	12.7	.163	.319	.535	192	326	360	192	326	360
		2+6F	8.7	10.3	11.8	.167	.318	.545	192	309	360	192	309	360
		2+SC	9.6	11.3	12.8	.165	.318	.535	192	326	360	0	0	0

11/ 1 HARVEST DATE

M.C.	CFM/BU		FINAL MOISTURE MIN	AVE	MAX	% DM DECOMP MIN	AVE	MAX	FAN HOURS MIN	AVE	MAX	HEATER HOURS MIN	AVE	MAX
20%	0.75	2F	12.2	13.5	14.6	.209	.243	.292	1326	2023	3006	0	0	0
		2+3F	12.7	13.3	14.1	.158	.210	.261	1200	1364	1974	1200	1200	1200
		2+6F	11.4	12.2	13.0	.155	.203	.267	1032	1102	1228	1032	1099	1200
		2+SC	11.8	13.4	14.1	.161	.214	.259	1200	1445	2296	0	0	0
22%	0.82	2F	11.1	13.0	14.4	.332	.424	.560	1396	2356	2992	0	0	0
		2+3F	11.9	13.3	14.0	.331	.403	.504	1200	1678	2684	1200	1200	1200
		2+6F	11.5	12.4	14.0	.298	.401	.522	1032	1241	1806	1032	1166	1200
		2+SC	11.8	13.5	14.4	.305	.397	.521	1242	1679	2670	0	0	0
24%	1.77	2F	12.5	13.3	14.5	.293	.402	.581	696	1241	2362	0	0	0
		2+3F	11.9	12.3	13.1	.260	.374	.624	528	746	864	528	746	864
		2+6F	10.9	11.5	12.9	.266	.369	.650	528	662	696	528	662	696
		2+SC	12.1	12.8	14.4	.265	.378	.612	696	910	1806	0	0	0
26%	2.78	2F	12.9	13.3	13.8	.296	.434	.707	528	840	1806	0	0	0
		2+3F	11.1	12.3	13.9	.297	.413	.694	360	578	696	360	578	696
		2+6F	10.0	11.7	14.1	.292	.404	.688	360	511	528	360	511	528
		2+SC	12.0	12.7	13.8	.293	.413	.692	528	645	864	0	0	0

TABLE 4. (CONTINUED)

MIDLAND, TEXAS (10 YEARS)

10/ 1 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
20%	0.92	2F	9.4	11.3	14.1	.259	.386	.537	696	796	864	0	0	0
		2+3F	8.6	10.5	13.0	.262	.388	.506	696	746	864	696	746	864
		2+6F	8.7	9.9	12.0	.269	.384	.496	528	645	696	528	645	696
		2+SC	8.3	10.3	12.9	.265	.388	.523	528	696	864	0	0	0
22%	2.01	2F	9.4	11.5	13.4	.229	.410	.677	360	528	1032	0	0	0
		2+3F	9.1	10.4	12.3	.220	.386	.644	360	427	528	360	427	528
		2+6F	8.5	10.0	11.9	.215	.367	.619	360	360	360	360	360	360
		2+SC	8.8	10.0	12.0	.214	.384	.669	360	427	528	0	0	0
24%	3.55	2F	9.0	11.2	12.9	.184	.426	.847	360	376	528	0	0	0
		2+3F	8.3	10.6	13.3	.173	.384	.675	192	343	360	192	343	360
		2+6F	7.7	9.8	12.4	.171	.360	.578	192	309	360	192	309	360
		2+SC	7.9	9.9	11.5	.171	.377	.642	192	343	528	0	0	0
26%	6.05	2F	8.8	10.7	12.8	.169	.394	.667	192	292	528	0	0	0
		2+3F	8.3	10.6	13.2	.171	.348	.564	192	225	360	192	225	360
		2+6F	7.7	10.1	13.1	.167	.320	.469	192	192	192	192	192	192
		2+SC	7.9	10.2	13.0	.167	.341	.555	192	225	360	0	0	0

10/15 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
20%	0.75	2F	9.0	11.9	13.3	.169	.274	.472	864	1015	1368	0	0	0
		2+3F	9.2	11.1	12.3	.174	.281	.476	864	931	1200	864	931	1200
		2+6F	8.1	10.4	11.7	.182	.287	.458	696	796	1032	696	796	1032
		2+SC	9.0	11.1	12.3	.173	.282	.469	696	897	1200	0	0	0
22%	1.30	2F	9.5	11.4	13.1	.195	.354	.636	528	729	1200	0	0	0
		2+3F	8.6	10.6	12.3	.204	.356	.632	528	612	864	528	612	864
		2+6F	7.9	9.7	11.3	.213	.355	.634	528	595	696	528	595	696
		2+SC	8.4	10.4	12.2	.206	.353	.631	528	612	864	0	0	0
24%	2.76	2F	8.0	10.9	13.8	.163	.340	.600	360	444	696	0	0	0
		2+3F	7.4	10.3	12.9	.168	.307	.522	360	393	528	360	393	528
		2+6F	6.9	9.7	13.0	.169	.298	.488	360	360	360	360	360	360
		2+SC	7.3	10.1	12.8	.173	.305	.497	360	393	528	0	0	0
26%	4.59	2F	7.8	10.6	13.7	.151	.319	.589	192	360	528	0	0	0
		2+3F	8.5	10.3	14.1	.152	.295	.500	192	309	528	192	309	528
		2+6F	7.8	9.8	13.1	.154	.284	.476	192	259	360	192	259	360
		2+SC	8.1	10.0	14.3	.153	.296	.500	192	292	528	0	0	0

11/ 1 HARVEST DATE			FINAL MOISTURE			% DM DECOMP			FAN HOURS			HEATER HOURS		
M.C.	CFM/BU		MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX
20%	0.75	2F	9.2	11.8	13.5	.141	.198	.259	864	1166	1368	0	0	0
		2+3F	8.9	11.1	13.0	.143	.205	.270	864	1015	1200	864	1015	1200
		2+6F	8.0	10.3	12.1	.142	.213	.282	864	931	1032	864	931	1032
		2+SC	8.8	11.1	13.4	.141	.205	.270	864	1015	1200	0	0	0
22%	0.82	2F	9.2	11.6	13.3	.271	.390	.529	1032	1267	1536	0	0	0
		2+3F	9.1	11.0	13.2	.273	.405	.559	864	1082	1368	864	1082	1368
		2+6F	8.0	10.2	12.3	.273	.424	.584	864	998	1200	864	998	1200
		2+SC	9.0	11.0	12.4	.274	.404	.549	864	1116	1368	0	0	0
24%	1.70	2F	8.4	11.5	13.9	.215	.374	.522	528	729	864	0	0	0
		2+3F	7.7	10.9	12.9	.225	.373	.544	528	645	696	528	645	696
		2+6F	6.9	10.0	11.8	.238	.373	.547	528	595	696	528	595	696
		2+SC	7.5	10.9	13.0	.227	.372	.542	528	612	696	0	0	0
26%	2.81	2F	8.8	11.8	14.2	.231	.382	.609	360	578	864	0	0	0
		2+3F	9.8	11.4	14.1	.237	.361	.528	360	494	696	360	494	696
		2+6F	9.0	10.7	13.0	.238	.352	.445	360	444	528	360	444	528
		2+SC	9.6	11.4	13.4	.237	.357	.512	360	494	864	0	0	0

TABLE 5. EXAMPLE OUTPUT FROM THE DRYCOST PROGRAM FOR DES MOINES, IOWA WITH 24% CORN HARVESTED OCTOBER 15 AND 2 F HEAT FROM THE FAN MOTOR.

GRAINDATA DES MOINES, IOWA
HARVEST 10/15 24% W.B. 2F

YEAR	FAN HRS	%DRY MATTER	AV MOIS	HEAT HRS
59	2074	0.335	12.360	0.
60	696	0.235	13.810	0.
61	1906	0.489	13.700	0.
62	696	0.327	13.960	0.
63	696	0.883	13.390	0.
64	864	0.389	14.200	0.
65	1892	0.596	13.320	0.
67	528	0.201	13.990	0.
68	2082	0.426	13.580	0.
69	696	0.212	13.920	0.
AVE	1213.	0.409	13.623	0.

COST ANALYSIS OF CORN DMI 05/19/78 09:29

MAN-CODE	HAR-DATE	MOISTURE	AIRFLOW	CORN-VALUE	FIXED-COSTS
2	1015	24 %	2.18 CFM	2.00	0.0

DIAMETER	BUSHELS	DEPTH	$/KW-HR	COLL-COST	LIFE	INTEREST-RATE
24.0 FT	6000.	16.6 FT	0.03	0.0 /SQFT	0 YEARS	0.0 %

COST OF DRYING CORN $/BU

	TOTAL	W/O ODRY	FAN	HEAT	SOLAR	SPOILAGE	OVERDRY
59	0.432	0.360	0.358	0.0	0.0	0.002	0.072
60	0.160	0.121	0.120	0.0	0.0	0.000	0.039
61	0.380	0.339	0.329	0.0	0.0	0.009	0.042
62	0.158	0.122	0.120	0.0	0.0	0.002	0.036
63	0.266	0.218	0.120	0.0	0.0	0.097	0.049
64	0.183	0.153	0.149	0.0	0.0	0.004	0.030
65	0.397	0.347	0.327	0.0	0.0	0.020	0.050
67	0.127	0.092	0.091	0.0	0.0	0.000	0.035
68	0.410	0.365	0.360	0.0	0.0	0.005	0.044
69	0.157	0.121	0.120	0.0	0.0	0.000	0.037
AVE	0.267	0.224	0.210	0.0	0.0	0.014	0.043

MINIMUM HORSEPOWER OF THE FAN IS 32.9
REQUIRED COLLECTOR SIZE (SQFT) IS 0.0
HEATER SIZE (KW) IS 0.0

Table 6. Effect of various levels of supplemental heat on the average drying costs (cents/bu) for several harvest date-moisture content combinations. These costs are based upon 10 years of simulated drying results. The airflow rates used for specific harvest dates, moisture contents and locations were taken from Table 2.

		ST. CLOUD, MINNESOTA HARVEST DATE			DES MOINES, IOWA HARVEST DATE			INDIANAPOLIS, INDIANA HARVEST DATE		
M.C.		10/01	10/15	11/01	10/01	10/15	11/01	10/01	10/15	11/01
20%	2F	9.1	10.2	12.0	7.3	8.7	9.9		12.7	11.6
	2+3F	9.7	11.2	12.4	11.2	10.6	11.2	11.2	11.1	10.6
	2+6F	14.2	11.5	12.6	15.3	14.4	12.3	15.4	13.6	11.9
	2+SC	14.9	16.8	19.4	14.5	14.2	16.8	16.9	15.5	16.7
22%	2F	14.1	12.3	13.0	11.6	11.8	12.6			25.2
	2+3F	14.6	13.5	13.9	16.6	13.5	13.8		14.4	16.3
	2+6F	18.7	14.0	14.6	21.3	18.2	14.7		17.2	15.3
	2+SC	23.2	20.0	20.4	27.3	21.8	14.7		22.0	20.3
24	2F		25.6	14.1			19.2			
	2+3F		22.5	14.8			19.1		23.0	26.7
	2+6F		24.6	16.9			20.7		22.8	25.6
	2+SC		39.6	20.6			26.1		35.4	36.4
26%	2F			26.1						
	2+3F			26.0						
	2+6F			26.2						
	2+SC			36.4						

		COLUMBIA, MISSOURI HARVEST DATE			MIDLAND, TEXAS HARVEST DATE			MACON, GEORGIA HARVEST DATE		
M.C.		10/01	10/15	11/01	10/01	10/15	11/01	10/01	10/15	11/01
20%	2F	8.6	7.4	7.2	11.5	9.5	9.8	11.7	9.4	6.8
	2+3F	12.7	11.1	9.9	15.5	13.6	13.8	14.6	14.1	11.4
	2+6F	16.8	15.1	14.7	18.3	16.7	17.6	19.1	17.5	15.7
	2+SC	16.6	13.8	12.9	21.3	17.6	17.4	24.7	20.2	14.8
22	2F	14.4	11.6	10.1	17.1	13.1	11.3			12.2
	2+3F	18.4	15.1	11.7	20.9	17.1	15.4			15.3
	2+6F	23.0	19.5	16.1	22.7	21.4	19.8			20.5
	2+SC	30.0	23.2	14.7	35.6	25.6	19.4			26.0
24%	2F			18.0			16.1			
	2+3F			19.8			20.4			
	2+6F			24.4			25.0			
	2+SC			30.7			30.6			

The results also indicate that drying costs were minimized for five of the six locations studied if no supplemental heat is added. For Indianapolis, the reduced airflow rates with supplemental heat, resulted in a lower drying cost. Regardless of this trend, it cannot be conclusively stated that supplemental heat should not be used. The study results will undoubtedly be different if other drying objectives or costs are considered. For example, if the corn is to be fed on the farm a penalty cost for overdrying probably should not enter into the economic analysis. If the grain is to be sold before spring, the additional cost of adding heat may be justified if it makes possible the completion of drying in the fall.

It is a common notion by many individuals, that natural air or low temperature grain drying is a simple operation. All an operator needs to do is fill the bin, turn on the fan and sit back and watch the grain dry. The complexity of the results presented in this paper should show that this is not true. In fact, a low temperature drying system will require a great deal of management. In years with unfavorable drying conditions, proper management will make the difference between successful drying or spoiling the grain. Thus, improved management techniques are important.

Improved System Management

Two of the major problems indicated by this study were the high airflow requirements for corn harvested at high moisture contents (especially when harvested early) and the excessive overdrying which occurs with the addition of supplemental heat.

Layer drying is being considered as one method of increasing the drying potential of a low temperature system. A layer drying approach can be used when the grain is being harvested at high moisture contents. However, the rate at which the bin can be loaded may become the limiting factor in the harvesting operation. Preliminary investigations have indicated that loading rate is probably the major factor influencing the performance of a layer drying operation. The effect of loading rate and other factors (harvest date, moisture content and year-to-year variations) are currently being investigated.

Managements which will reduce the amount of overdrying are also receiving considerable attention. Several methods are available to try to reduce this overdrying. Three areas currently being studied are stirring the grain, reversing airflow direction during low humidity drying periods and recycling some of the high humidity exhaust air. The study is still in the initial stages, but early results indicate that reductions in overdrying may be difficult to achieve. One problem is that, with the exception of stirring, these methods tend to slow the drying process and increase the chances of spoilage. Stirring appears to have a positive effect upon the drying process but may not be desirable from the energy required or economic viewpoints. Additional study is progressing to resolve these issues.

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SOLAR ENERGY APPLICATIONS TO CROP DRYING

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This research program, funded in part by DOE, for the application of solar energy to the drying of crops other than grain, consists of eight project locations. Tobacco curing, which is second only to grain in fuel requirements for drying, is being investigated at three locations, peanut and forage curing are being investigated at two locations each, and the development of low-cost collector-storage systems designed specifically for agricultural use is being conducted at one location. Although these projects may be currently concentrating on a specific application, all are aware that additional uses of the collector-storage system will reduce the cost of solar energy drying and speed its adoption.

The tobacco curing research with solar energy at North Carolina State University is focused on the use of a greenhouse for the collection and storage of solar energy. The greenhouse is constructed so that portable bulk curing bins can be installed during the tobacco curing season. The outside of these bins is painted black to increase energy absorption. Additional energy absorbing surface is obtained by painting the surface of the gravel storage black. Heated air is pulled down through the gravel to increase storage capacity. The use of this system has reduced the fuel requirement for tobacco curing by 35-40 percent.

When the curing season has ended, the curing bins are removed and the structure is used for the production of conventional greenhouse crops. It is estimated that fuel savings of 10-15 percent are realized when the unit is used as a greenhouse. Tobacco transplants are produced in multiple layers for automatic transplanting. Germination rates ranged from 95-97 percent for the various layers. This year, a specially designed drier for peanuts will be installed in the structure to evaluate the potential for peanut drying.

The application of solar energy to the curing of tobacco by the USDA and the University of Kentucky consists of a two-stage system. The tobacco is solar field cured for two days and then placed in a barn which is heated by solar energy to reduce the relative humidity to the 65-70 percent range. For the experimental facility, flat-plate solar collectors are built into the roof and a limestone rock storage bed is utilized to store the heat. The solar collector-rock bed system supplied enough heat to maintain the relative humidity at the desired 65-70 percent level for 3 or 4 days.

At the Georgia Coastal Plain Experiment Station, an existing solar collector and crushed rock storage system will be utilized in an effort to cure tobacco without the use of petroleum fuel. The heat requirements for all except the stem drying phase (74°C) can be met from solar energy stored in the rock bed. The supplemental energy will initially be supplied by LP gas. The curing regime will be established so that the high temperature phase can come during off-peak hours for the electric system. This will allow electric heat pumps to be used to amplify the stored solar energy to eliminate the dependence on petroleum products.

At the Oklahoma State University, the use of a 1400m^3 fresh water pond to store solar energy is being investigated. The pond is lined with butyl rubber and enclosed in a polyethylene dome to store water heated to 44°C by solar energy. Heating begins about August 1 and extends through the November peanut drying season. The surface of the pond and a separate flat-plate collector are used to collect solar energy. Problems were encountered with the strength of the seams in the polyethylene dome last year and the desired temperature was not attained.

The peanut research at Tifton involves the use of solar energy collected by both air and water. Model bins containing 0.45 m^3 of peanuts (1/28 wagon size) were used for these studies. Solar heated air was used without storage by allowing cyclic temperature drying. During periods of little or no insolation, LP gas was used to maintain a drying potential of the air. Solar energy stored in water was used to heat the drying air through a heat exchanger. The use of solar energy reduced the amount of LP gas necessary by various amounts, depending upon the test. In some instances, all the heat energy required for drying was supplied by solar. In other tests, solar energy was able to supply as little as 20 percent.

A full-scale drying shed with flat-plate collectors built into the roof was completed at the end of the '77 peanut drying season. This unit has 70 m^2 of water collector, 70 m^2 which can use either water or air for the collecting medium and 140 m^2 which can use air only as the collecting medium. Heat from the air collectors is stored in 110 tonnes of crushed granite. Water storage of approximately 10,000 liters is available for the water system. Temperature of the air from the rock storage is controlled by modulating vanes and a proportional controller. A heat exchanger is used to utilize the solar energy stored in water. This unit will also be used to dry small grains, grain sorghum, corn, pecans and other crops, in addition to furnishing heat for tobacco curing.

Solar energy is being used by the University of Tennessee to dry large packages of hay. Both large round bales and small stacks can be dried by this system. The capacity of the system is two small stacks and five large round bales (approximately 5.5 tonnes total). Solar energy is gathered by an integral roof collector to which glazing has been added and by a free-standing collector. The overall efficiency of the two systems was 56 percent for the free-standing collector and 44 percent for the integral collector (unglazed at the time of the tests). The drying rate of the hay is highly dependent upon the density of the package. The higher density packages dried too slowly to obtain throughputs required for economical operation. A search is underway for better methods of ventilating the higher density packages.

At Colorado State University the potential of utilizing solar energy, collected by flat-plate collectors, for the dehydration of forage crops is being investigated. Here, alfalfa tops, whole plant alfalfa and grass clippings were dried by: (1) high temperature dehydration, (2) solar dehydration, or (3) sun curing. The high temperature dehydration and sun curing treatments both resulted in reduced protein content in all forage types. The lutein content (an indicator of xanthophyll, which is a pigmentation agent) loss by either dehydration method was only about one-half that of the sun curing method. These products have been fed as an additive to a poultry ration and results are now being analyzed.

The research program at Georgia Tech has evaluated several materials, ranging from glazing, through absorbing surfaces and storage media, used for solar energy collector-storage systems. Based on these studies an Augmented Integrated Rock System (AIRS) has been designed and tested. A 111.4 m^2 AIRS has been built. This system has a 66.9 m^2 black film hot air collector tilted 35° to the south and a 44.5 m^2 integrated rock bed tilted 5° to the south. Energy collected in both the black film collector and the integrated rock bed is stored in the rock bed. With a ΔT of 38°C, about one billion joules of energy can be stored in this unit. The material cost is about \$21.00/m^2 for the black film collector and about \$10.75/m^2 for the integrated rock collection and storage portion.

Of the crops currently being studied, hay presents the longest drying season. The season for drying most crops is very short and specific. Consequently, it will be necessary to develop multiple uses of the solar collector-storage system in order to make solar energy economically attractive to a large enough number of users for it to have a significant impact on our energy consumption. Thus, any integration of uses between the various research programs will be of significant benefit.

WHEAT-DRYING COSTS FOR SOLAR AND ALTERNATIVE DRYING SYSTEMS

M.L. Haas, J.R. Barrett and W.E. Tyner [1]

Double cropping of winter wheat followed by soybeans has expanded rapidly in the Midwest during the past few years, becoming a profitable alternative to corn. Earlier planting of soybeans than is otherwise possible is allowed by harvesting of wheat at high moisture contents (m.c.). For each day that planting can be moved up, the resulting yield of soybeans can be increased as much as three-fourths bu/a by taking advantage of the longer growing season and higher subsoil moistures (Barrett et al. 1978). However, when wheat is harvested at a high m.c. it must be artificially dried to insure safe storage.

Since most wheat is not artificially dried, but allowed to dry in the field, very little research has been done on the costs of drying the wheat to 13.5% m.c. wet basis (w.b.) which is the safe level for storage.

This paper develops and presents fixed and variable in-bin wheat drying costs using information from on-farm research experience and present construction and materials cost. The effects of larger bin diameters and capacities, along with the effects of equipment purchased for the sole use of drying wheat are considered. Cost differences attributed to alternative heat sources are included with emphasis on low energy solar and natural unheated air systems in contrast to liquid petroleum (LP) gas systems. This paper is arranged in three sections, the first is on fixed costs, the second is on variable drying costs under both present and increased energy prices, and the third section presents the maximum price that can be competitively paid for a solar collector.

Drying costs are broken down into two categories. These follow the recommendations of Barrett et al. (1978). The first category was concerned with drying wheat from about 25% to 13.5% m.c. For this category, three methods of drying were chosen: 1) Drying with solar heated air (30 F peak temperature rise over ambient): 2) drying with air heated by LP gas (40 F rise): or 3) a combination of drying to 19% with air heated by LP gas followed by drying with natural, unheated air to 13.5%. Natural-air drying alone was not considered for wheat with an initial m.c. above 20%, because the moisture removal capacity of unheated air is too low to dry the wheat to a safe level before spoilage occurs.

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The second category was concerned with drying wheat from about 19% to 13.5%. Three methods were also chosen for this category, as follows: 1) Drying with air heated by LP gas (40 F temperature rise over ambient), 2) drying with natural, unheated air, or 3) drying with solar-heated air (30 F peak temperature rise). Drying with unheated air only was considered safe if the initial m.c. was below 20%.

FIXED COSTS

The in-bin drying of high-moisture wheat requires essentially the same equipment as is needed for drying corn. The components of a drying system are basically the drying bin, fan, heat source, bin filling, and unloading equipment, stirring device, and moisture meter. Although stirring devices are not essential for most corn drying, their use in drying wheat is important due to the greater potential for mold development at summertime temperatures. When stirring devices are used, the probability of wheat spoilage is decreased, as the relatively high-moisture wheat at the top of the grain mass and the drier grain at the bottom are mixed. The result is a nearly homogeneous grain mass with no layers or pockets of wet grain. Also, stirring the grain reduces the problem of overdrying.

In the determination of fixed costs, four situations were chosen. In the first, all of the components of the drying system were assumed to have been purchased for the exclusive use of drying wheat. In the second, a storage bin was assumed to be available for wheat drying. Here, total fixed costs consisted of the incremental cost of adding a perforated floor, drying fan, LP gas burner, and stirring device. In the third, a storage bin equipped with fully perforated floor for aeration was assumed to be available. For this situation, fixed costs included only the incremental costs of adding a drying fan, LP gas burner, and a stirring device. In the last situation, all of the drying components except the stirring device were assumed to be available. Therefore, fixed costs included only those costs directly attributable to the stirring device.

For farmers who have a complete drying system, all fixed costs were assumed to be allocated to corn drying. Fixed costs for the solar method consider the solar collector to be purchased for drying corn. Therefore, in all instances all the fixed costs relating to the solar collector were allocated to corn drying. Implicit in these assumptions is the additional assumption that the collector or bins would not be in use during wheat drying.

The actual components of fixed costs were: 1) Depreciation, 2) interest, 3) taxes, 4) insurance, and 5) repairs. Although repairs are often thought of as a variable cost, they were included as a part of fixed costs by assuming that most of the deterioration requiring repair would not be caused by actual use, but rather by weather or by damage such as caused by backing a tractor into the fan.

Depreciation was calculated on a straight-line basis, and the same cost was assumed for each year. The grain bins and drying fans in all instances were assumed to have a 20-yr lifetime, and the stirring devices, augers, and moisture meters were assumed to have a 10-yr lifetime.

Interest was computed on the basis of borrowing the full amount for the purchase of the grain bin and/or equipment, and the interest rate assumed was 8% /yr with an added service charge of 1% for the first $20,000. The interest portion of fixed cost was calculated by multiplying the interest rate times half the total purchase price of the incremental drying equipment (Schwart and Hill 1977). The half-price value used was considered to represent the average value of the equipment.

Property taxes were calculated only on the equipment attached to the ground (bin, drying fan, and stirring device). No tax was computed for the moisture meter and augers. The actual property tax was calculated as 30% of the attached equipment times a tax rate of $7/$100 assessed value. From this amount, a replacement credit of 20% was subtracted. It was assumed that the decrease in the book value of the grain system over its usable lifetime would not be reflected by a decrease in its assessed value. Therefore, the property tax was assumed to be constant.

Insurance was calculated as 0.5% of the original cost of the equipment/yr. The insurance cost represented what an average premium would be for protection against wind, water, fire, lightning, and tornado damage for an Indiana farmstead. It was assumed that the premium would remain constant over the lifetime of the bin.

Repair costs were figured as 1% /yr for the grain bins and drying fans, 3% /yr for the stirring devices and augers, and 10% /yr for the moisture meter. It was assumed that the cost of repairs remained constant, as the relatively higher costs of repairs in the later years were averaged with the relatively lower costs in the first few years.

VARIABLE COSTS

Variable costs were determined for three wheat drying methods at two initial m.c. For drying from about 25% to 13.5%, the three methods were: 1) Drying only with LP heated air (40 F temperature rise), 2) drying with LP heated air to 19% (same temperature rise), and completion of drying with unheated air, and 3) drying with solar heated air (30 F peak temperature rise). For drying from about 19% to 13.5%, the three methods were: 1) Drying only with LP heated air (40 F rise), 2) drying with unheated air, and and 3) drying with solar heated air (30 F peak rise).

Variable costs included LP gas, electricity for fan and stirrer operation, tractor pto operation, and labor for running the augers during filling and loading operations, labor for checking the drying progress, and for bin preparation (cleaning and repairing the bins, servicing fans and adjusting burners). These costs were derived from 1975-77 drying tests at Purdue University.

LP GAS COST

In determining LP gas usage, data were taken from the 1977 drying tests. Since these were the only data available, the LP portion of variable costs for this one year was assumed to represent the LP cost/bu during any year. In addition, since data were limited to a single bin, it was assumed that the different bin diameters and fan sizes would have about the same LP cost/bu and that bins had airflow rates of 2.5 cfm/bu.

According to the 1977 test data, 1657 (13.5% w.b.) of wheat were harvested at an average of 24.7% and dried to 19.0% in a 22-ft diam bin using a 7.5-hp fan and LP gas heat at a 40 F temperature rise. At 24.7% the wheat consisted of 86,027 lb of dry matter and 28,169 lb of water. When dried to 19.0%, this wheat consisted of the same 86,027 lb of dry matter, but only 20,179 lb of water. Therefore, in the 30 h that the wheat was dried with heated air, about 7990 lb of water were removed.

Because no meter was available for measuring LP gas usage, several calculations were made to estimate that usage. The first calculation involved separating the drying effect of the ambient air from the drying caused by LP heated air. To accomplish this, data were used from another simultaneously run experiment that involved drying about 1421 (at 13.55) bu of wheat in an 18-ft bin using a stirring device. To that experiment, data taken about 45 h apart indicated a m.c. reduction from 19% to 17.7%. This

1.3% reduction translated into about 1438 lb of water removed. Assuming that the rate of water removal was constant over the 45 h period, then 32 lb of water were removed during each h /1421 bu dried.

Assuming this water-removal rate to be representative of the drying effect of the ambient air during our LP gas drying situation, then about 1125 lb of water should have been removed solely as a result of the drying effect of the ambient air. Subtraction of the water loss caused by the ambient air from the total water loss resulted in about 6865 lb of water having been removed by the heat from the LP gas.

For calculation of the LP gas usage, the conventional assumption was made that 1200 Btu's would be needed to remove a lb of water from a grain mass and that 1 gal of LP gas would contain about 90,000 Btu's of heat. However, a substantial portion of the heat potential in 1 gal of LP gas is never utilized in drying because of system losses and incomplete exhaust air saturation. An efficiency of 60% was assumed which approximates the efficiency of an in-bin gas dryer (Foster 1978). Total LP gas usage was calculated to be 0.0269 gal/percentage point moisture removed/100 lb. A linear drying rate was assumed for drying the wheat from 25% to 19%. At m.c. below 19%, drying rates are reduced due to rewetting and/or slower drying during night hours. As a result, LP usage was assumed to take 10% more time and more gas for drying from 19% to 13.5% than from 25% to 19%. On that basis 0.0296 gal of LP would be used to remove each point of moisture from each 100 lb of wheat as sold at 13.5%.

Total LP gas usage is therefore made by multiplying the number of 100-lb increments of grain mass that has been dried times the number of points of moisture removed times 0.0269 for 25% to 19%, or times 0.0296 for drying from 19% to 13.5%. For arrival at the cost/bu this amount was then multiplied by the LP cost/gal, and divided by the total number of dried bu.

COST OF ELECTRICITY FOR FAN OPERATION

A major portion of variable costs in low-temperature in-bin drying is attributable to the cost of electricity for operation of the fan that blows air though the grain. Drying times as determined from actual drying tests with LP, solar, and natural air experiments and related simulations, were as follows: 1) For drying from 25% to 13.5% 336 h with solar heat, 582 h with the LP/natural, unheated air combination and 108 h with the LP heat; and 2) for drying from 19% to 13.5%, 192 h with solar heat, 552 h with natural, unheated air, and 78 h with LP heat. With each type of drying, the airflow rate was 2.5 cfm/bu.

In addition to the fan operating time, it was assumed that the fans ran about 48 h while the bins were being filled. Although the fan is off during the loading of the first few bu of wheat, it must be turned on immediately thereafter to cool the grain.

The determination of the electrical usage by the drying fan was calculated by multiplying the hp of the fan times 0.745 kw/hp (Foster 1977) times the number of h of use. The total electrical cost for fan operation/bu is in Table 3.

COST OF ELECTRICITY FOR STIRRING

The stirring cost was calculated assuming that operation was continuous when the drying fan was operating. The stirring-device motor was assumed to be 1 hp for bins up to and including 27 ft in diam. A 1.5-hp motor was assumed in the 30-ft diam bin. The cost/bu for stirring is in Table 3.

LABOR COST

Labor costs were calculated on the basis that only the extra labor required for the actual drying would be included. Therefore, no labor costs for the harvesting or the movement of the grain from the fields to the farmstead were included. Basically, the labor for which costs were calculated consisted of that used for filling and unloading the bin, checking the drying progress, and preparing the bin. The labor cost used for all the operations was $5/h. Although many farmers would not 'charge' for their own labor, their labor was included to serve as a benchmark that may be adjusted for individual situations.

Because of the high m.c. of the wheat, bin filling is a relatively slow process. Therefore, it was assumed that only 425 bu/h could be moved with a 6-in. auger and 850 bu/h with an 8-in. auger. Ideally, two persons are needed for the filling operation, one to control the flow of the wet grain into the auger and the other to guide and push the grain to the outlet of the wagon or truck bed. However, hiring an extra person for the few h needed would be unreasonable. The labor cost/bu of wheat loading was $0.0118 for the 6-in. auger, and $0.0059 for the 8-in. auger.

To determine the costs to operate the auger during unloading the grain, it was assumed that a 6-in. auger can removed 850 bu/h from the bin and that an 8-in. auger can remove 1700 bu/h. A 1.5-hp motor was assumed to power either augers. Therefore, the operating cost of unloading the wheat from the bin using the 6-in. auger would be $0.0059/bu, while the cost of operating the 8-in. auger would be $0.0029/bu.

It was assumed that one person would be required for 2h/season to prepare each of the drying systems. Assuming a $5.00/h rate, preparation costs would be $10/bin/season.

The remaining labor cost consisted of the checking of the grain for m.c. and for spoilage or insect damage. This was assumed to require about 15 min/day.

TRACTOR PTO

For determination of tractor PTO costs, it was assumed that the operation of a 50- to 90-hp tractor to load the grain would cost $1/h (Parsons 1978). The cost of PTO operation/bu were calculated by dividing the $1 by the capacities of the 6- and 8-in. augers for both filling and unloading. The resulting cost was $0.0036/bu using a 6-in. auger or $0.0018/bu using an 8-in. auger. The 18- to 21-ft diam bins were assumed to need a 6-in. auger, while the 24- to 30-ft diam bins need an 8-in. auger.

EFFECT OF INCREASING ENERGY PRICES

A computer program was written to determine the effect of increasing energy prices on variable costs. Electricity rates were increased from $0.0177/kwh in 10% increments. For each rise in the price of electricity, an LP price was calculated which would make the cost/bu of a system using LP gas equal to the cost/bu of either the natural air system (for drying from 19% to 13.5%) or the LP assisted, natural air system, (for 25%-13.5%). The results of this program are in Figures 1 and 2 showing which system is economically superior at different LP and electricity costs. Figure 1 should be used to help decide between the LP/natural system or LP system for wheat dried from 25% to 13.5% m.c. Figure 2 should be used to help decide between the LP or natural unheated air systems for wheat dried from 19% to 13.5%. By projecting the current electricity rate upward from the horizontal axis to the current LP price projected from the vertical axis, the point of intersection provides the solution as to which system is most economical. For cases where the intersection is to the right of the diagonal line, a system using more LP gas and less electricity for unheated air ventilation is less expensive. For cases where the intersection lies to the left of the line, a system utilizing more natural, unheated air drying is less expensive.

In all systems recommended for use in drying from 25% to 13.5% (Figure 1), the system with the lowest variable cost also had the lowest total cost. However, for drying from 19% to 13.5% (Figure 2), the system with the lowest variable cost was not necessarily the most overall economical system, as the extra fixed costs of the LP burner could result in a higher fixed cost for the LP system. Therefore, in some cases a LP system had the lowest variable costs and a higher overall cost.

DETERMINING MAXIMUM COLLECTOR COST

So far no value has been included for collector purchase. The solar costs consist only of the variable handling and fan operation costs using a collector giving a peak 30 F temperature rise, and the fixed costs associated with the drying bin and associated equipment. To determine the maximum price that could be economically paid for a collector, a computer program was written using the results derived from the first two sections of this analysis. By subtracting the total cost/bu for solar wheat drying from the equivalent cost of an alternative system, and multiplying the difference by the number of bu to be dried, the maximum amount/yr that can be competitively paid for a solar collector can be determined.

Fixed costs were determined on a 10-yr life basis for the collector, with an interest rate of 9% /yr (actually calculated as 4.5% /yr, representing the average interest payment), with no property tax or insurance, and for a 0.5% /yr repair cost. This results in an annual fixed cost rate for a collector of 15% /yr. By multiplying the total bu to be dried by the difference in solar drying and alternative system cost and dividing this total by the 15% fixed cost rate for the collector, the result will be the maximum competitive price that can be paid for a solar collector.

As an example, assume a decision is made to dry 4,060 bu of 25% wheat to 13.5% in a 30-ft diam bin. The options available are to use either a solar, LP and natural air, or LP heated system. The variable cost/bu for the systems are respectively $0.0332, $0.0877, and $0.0985 using current energy prices. Therefore, the solar drying costs $0.0545/bu less than the LP/natural air and $0.0653 less than the LP only. Since 4,060 bu are being dried, total variable cost savings would amount to $221 when compared with the LP/natural system, and $265 when compared with the LP only system. Dividing total variable cost differences by the annual fixed cost rate (15%) gives a maximum collector cost of $1,475 when compared to the LP/natural case, and $1,767 when compared to the LP only case. These two collector costs represent the maximum competitive price that can be paid for a solar collector for drying wheat at current energy prices ($0.0177/kwh for electricity and $0.0405/gal of LP).

The effect of increasing the price of LP and electricity showed that a solar collector is worth more where wheat is dried from 25% to 13.5%. For example, in the case where electricity cost $0.0372/kwh and LP cost $0.405/gal, a solar collector in a 24-ft diam bin was determined to be worth about $1267 when compared with the LP/natural air case, while the same collector for drying from 19% to 13.5% was worth $821.

The capacity of the system as related to bin diam (as all bins were considered filled to maximum as limited by 2.5 cfm/bu airflow) also had an effect on the maximum economic collector cost. For energy prices at this writing, a solar collector for an 18-ft diam bin, would be worth $660 and $1475 for the 30-ft diam bin when compared to a LP/natural system. For the case where electricity costs $0.0496/kwh the maximum economic collector cost for the 18- and 30-ft bins are $989 and $2072 respectively. Comparing these two prices, it is apparent that increases in energy prices result in a greater difference in maximum economically competitive collector prices, as associated to bin size. Therefore, as energy prices rise, a solar collector will become more feasible for a larger capacity bin.

The increase in maximum collector prices as electric rates were raised, was not as large as anticipated. For example, when electricity rates were quadrupled to $0.0513/kwh, (with LP prices held constant), the difference in competitive collector prices for a 27-ft diam bin was only $367 when compared to LP/natural case and only $539 when compared with natural air only. For the case where the price of electricity was kept constant and LP prices quadrupled, the maximum price one could economically pay for a collector (when compared to the LP case) rose substantially. For example, the maximum collector price for the 18-ft bin rose from $552 to $2916, and from $1767 to $8165 for the 30-ft bin.

These results are based on a collector that heats all the air blown through the grain a peak temperature rise of 30 F. By changing the collector size, the effects of changes in energy prices could be substantially different. As we have presented the relationships, changes in LP prices have a substantial impact on the economic attractiveness of the collector while changes in electricity prices are not as important. This is explained for the most part by the amount of use of electricity for fan operation in the solar case. At the present high capital costs of solar installations, it appears that solar collectors will become economically feasible when LP gas prices increase and not when electric prices rise.

RESULTS AND DISCUSSION

Tables 1 and 2 contain a summary of the fixed costs incurred with each drying system for five bin sizes. The results shown indicated that the fixed costs/bu of wheat dried decreased for every type of system as bin diameters increased.

Table 3 contains the variable wheat drying costs using the local energy prices for the fall of 1977 of $0.405/gal of LP and $0.0177/kwh of electricity.

For all drying systems, the total drying cost/bu (Table 4) decreased as bin size increased. The bulk of the change is attributable to declining fixed costs/bu. Although variable costs also decreased with the larger bin capacities (Table 3), they accounted for less than 10% of the decline in total drying costs/bu.

Fixed costs attributed to equipment that was purchased solely for wheat drying, had a substantial influence on total drying cost/bu. Differences in total costs between purchasing a complete system for wheat drying and having the system on hand ranged from a high of 93 cents to zero (for no incremental purchases), representing a range of about 90% to 0% of total drying costs/bu. As a result, a large portion of the potential for lowering total wheat drying cost is in decreasing the fixed cost/bu through multiple-use of the drying facilities.

Energy prices dictate which drying system is the most economical. At current energy prices, the results favor the use of LP/natural air drying systems in bins 24 ft or more in diam (for wheat dried from 25% to 19%). For wheat dried at a beginning m.c. of 19% or less, natural air drying exhibited lower costs/bu for all bins. Any change in the LP to electricity price relationship may result in different optimum systems. Figures 1 and 2 point this out.

Maximum economically competitive collector costs were determined to rely heavily on LP gas costs, as changes in price of electricity had a relatively small effect. In some cases where electricity was quadrupled the

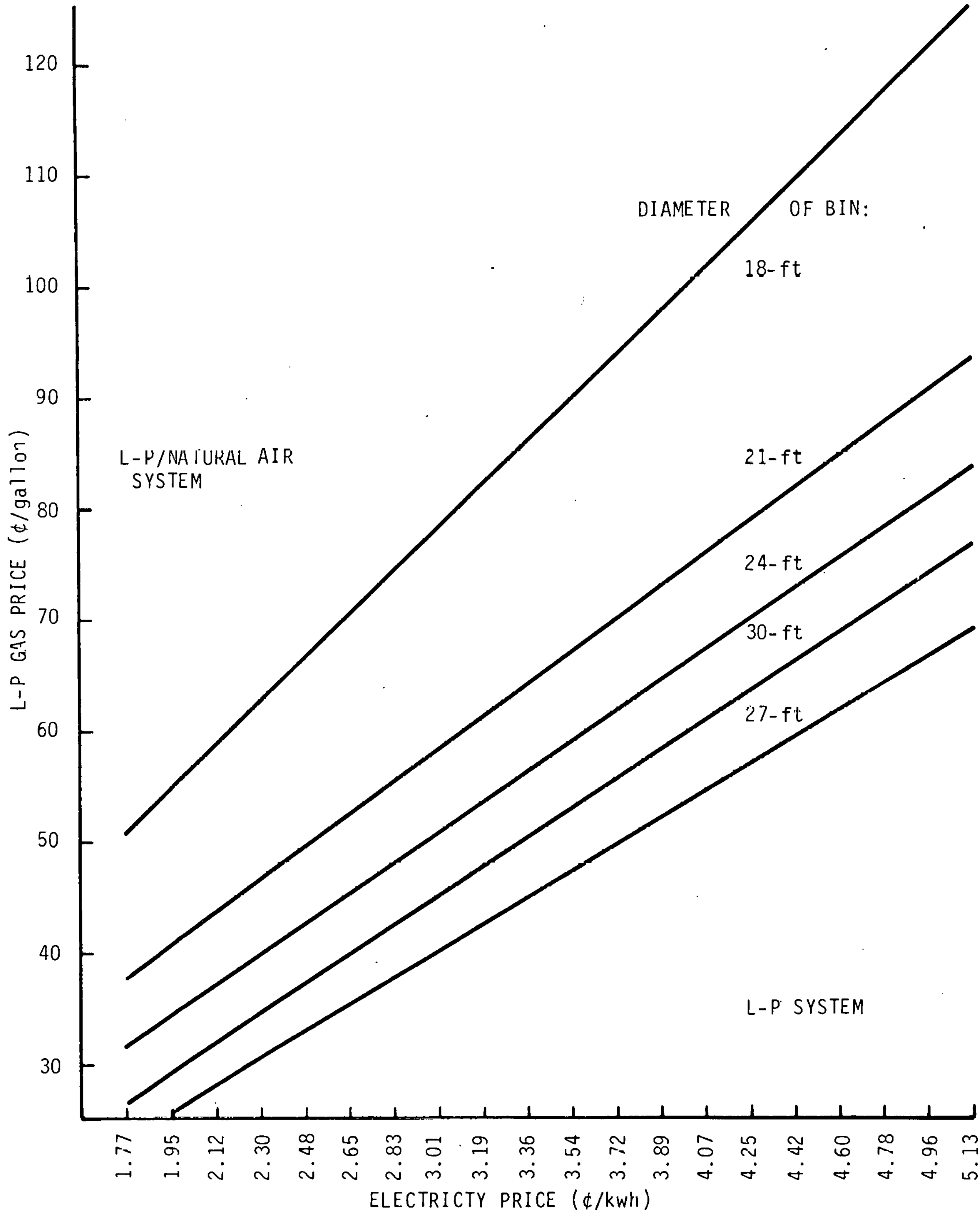

Figure 1. Economic relationship of variable costs of drying wheat expressed in terms of L-P and electric energy prices for the L-P/natural unheated air system vs. the L-P system for drying wheat from 25 to 13.5% w.b.

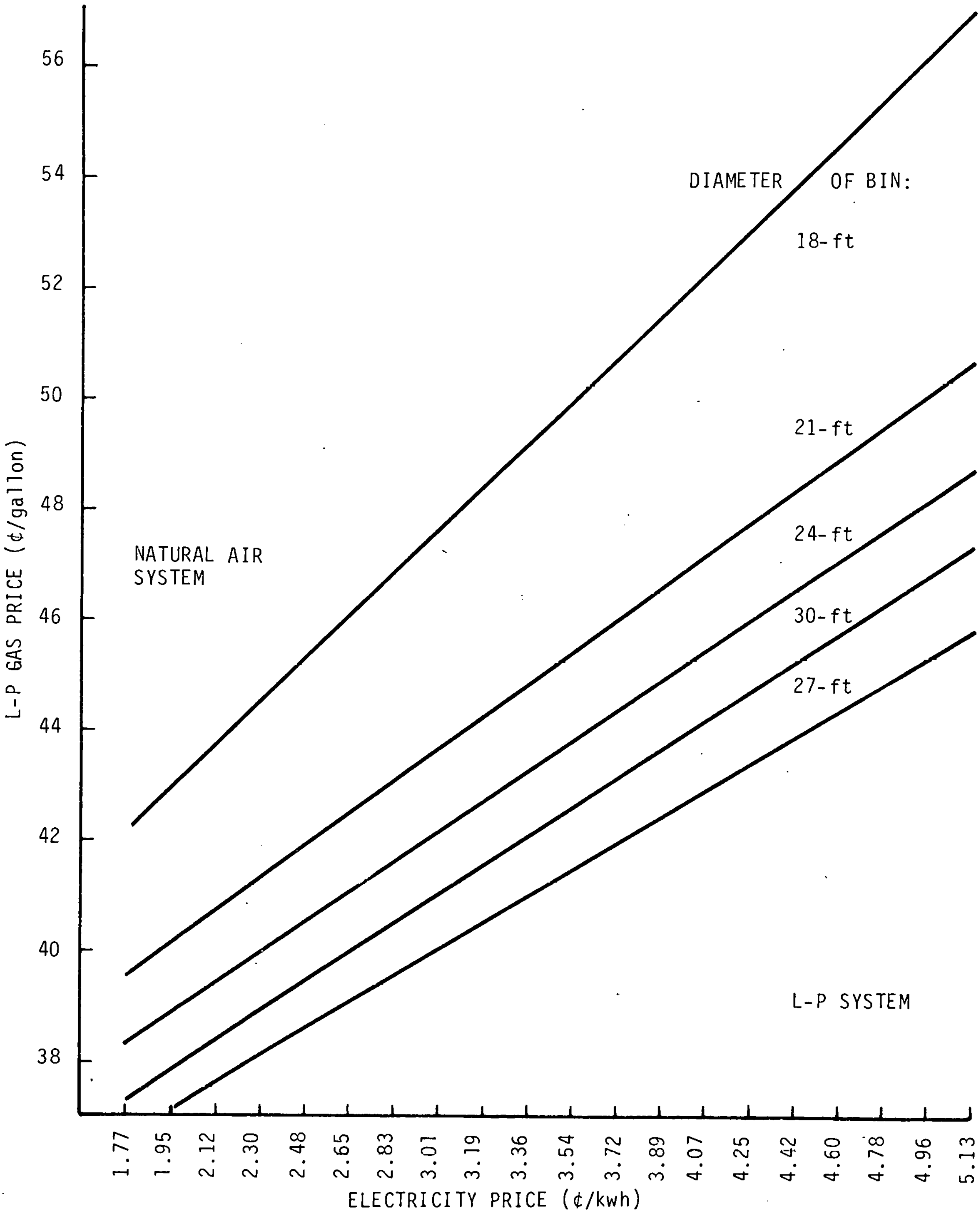

Figure 2. Economic relationship of variable costs of drying wheat expressed in terms of L-P and electric energy prices for the natural unheated air system vs. the L-P system for drying wheat from 19 to 13.5% w.b.

maximum economic collector cost rose less than $1000 whereas when LP prices were quadrupled it rose more than $7000.

In addition, since this research considered a data base from only one size collector with a peak of about 30 F temperature rise, different sizes of collectors should be considered.

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Table 1. Annual fixed costs of wheat drying systems.

Component	Complete system to be purchased: LP heated	Complete system to be purchased: Natural or solar*	Storage bin available: LP heated	Storage bin available: Natural or solar*	Aeration bin available: LP heated	Aeration bin available: Natural or solar*	System on hand except stirring device
18-ft diam bin with 7-hp fan:							
Depreciation	$607.70	530.30	355.10	277.70	326.10	248.70	141.00
Interest	387.41	352.58	188.82	153.99	147.87	113.04	63.45
Insurance	43.05	39.18	20.98	17.11	16.43	12.56	7.05
Repair	206.14	182.92	106.68	83.46	98.58	75.36	42.30
Tax	144.63	131.63	70.49	57.49	55.20	42.20	23.69
Total	$1388.93	1236.61	742.07	589.75	644.18	491.86	277.49
21-ft diam bin with 7-hp fan:							
Depreciation	$691.55	614.15	530.78	453.30	328.30	250.90	146.70
Interest	450.81	415.98	182.16	147.33	147.74	82.57	66.02
Insurance	50.09	46.22	20.24	16.37	16.42	12.55	7.34
Repair	233.95	210.73	106.14	129.36	98.49	75.27	44.01
Tax	131.61	118.61	68.01	55.01	55.15	42.15	24.65
Total	$1558.01	1405.69	907.25	801.37	646.10	463.44	288.72
24-ft diam bin with 9-hp fan:							
Depreciation	$803.90	723.90	445.25	365.25	400.00	320.00	202.90
Interest	525.11	489.11	220.73	184.73	180.00	144.00	91.31
Insurance	58.35	54.35	24.53	20.53	20.00	16.00	10.15
Repair	265.48	241.48	129.05	105.05	120.00	96.00	60.87
Tax	159.35	145.91	82.40	68.96	67.20	53.76	34.09
Total	$1812.19	1654.75	901.96	744.52	787.20	629.76	399.32
27-ft diam bin with 9-hp fan:							
Depreciation	$920.35	840.35	469.25	389.25	409.50	329.50	212.40
Interest	606.74	570.74	238.05	202.05	184.28	148.28	95.58
Insurance	67.42	63.42	26.45	22.45	20.48	16.48	10.62
Repair	293.92	269.92	134.80	110.80	122.85	98.85	63.72
Tax	183.10	169.66	88.70	75.26	68.80	55.36	35.68
Total	$2071.53	1914.09	957.25	799.81	805.91	648.47	418.00
30-ft diam bin with 13-hp fan:							
Depreciation	1021.65	941.65	553.00	473.00	485.50	405.50	240.30
Interest	684.50	648.50	279.23	243.23	218.48	182.48	108.14
Insurance	76.06	72.06	31.03	27.03	24.28	20.28	12.02
Repair	326.78	302.78	159.15	135.15	145.65	121.65	72.09
Tax	212.13	198.69	104.24	90.80	81.56	68.12	40.37
Total	$2321.12	2163.68	1126.65	969.21	955.67	798.03	472.92

* No LP dryer or solar collector fixed costs included.

Table 2. Annual fixed costs per bushel of wheat drying systems.

Initial moisture content	Complete system to be purchased: LP heated	Complete system to be purchased: Natural or solar*	Storage bin available: LP heated	Storage bin available: Natural or solar*	Aeration bin available: LP heated	Aeration bin available: Natural or solar*	System on hand except stirring device
18-ft diam bin with 7-hp fan:							
25%	$.9260	.8244	.4947	.3932	.4295	.3279	.1850
19%	.8627	.7681	.4609	.3663	.4001	.3055	.1724
21-ft diam bin with 7-hp fan:							
25%	$.8031	.7246	.4677	.4131	.3330	.2389	.1488
19%	.7455	.6726	.4341	.3834	.3091	.2217	.1381
24-ft diam bin with 9-hp fan:							
25%	$.6838	.6244	.3404	.2810	.2971	.2376	.1507
19%	.6381	.5827	.3176	.2622	.2772	.2217	.1406
27-ft diam bin with 9-hp fan:							
25%	$.6533	.6038	.3020	.2523	.2542	.2046	.1319
19%	.6075	.5613	.2807	.2345	.2363	.1902	.1226
30-ft diam bin with 13-hp fan:							
25%	$.5717	.5329	.2775	.2387	.2355	.1966	.1165
19%	.5324	.4963	.2584	.2223	.2193	.1830	.1085

*No LP dryer or solar collector fixed costs included.

Table 3. Variable costs per bushel for drying wheat with various drying systems, starting at 25% or 19% moisture content.

Component	To dry from 25 to 13.5%			To dry from 19 to 13.5%		
	Solar	LP gas + air only*	LP gas	Solar	Unheated air only	LP gas
18-ft diam bin with 7-hp fan:						
LP Gas	$----	.0395	.0788	-----	-----	.0395
Fan operatin	.0207	.0358	.0066	.0110	.0316	.0045
Stirring	.0030	.0051	.0009	.0016	.0045	.0006
Tractor, fill & unload	.0036	.0036	.0036	.0036	.0036	.0036
Labor to:						
Fill bin	.0118	.0118	.0118	.0118	.0118	.0118
Unload bin	.0059	.0059	.0059	.0059	.0059	.0059
Check progress	.0117	.0208	.0042	.0062	.0179	.0031
Prepare bin	.0067	.0067	.0067	.0062	.0062	.0062
Total cost/bu	$.0632	.1289	.1185	.0462	.0815	.6752
21-ft diam bin with 7-hp fan:						
LP Gas	$----	.0395	.0788	-----	-----	.0395
Fan operation	.0160	.0277	.0051	.0085	.0244	.0035
Stirring	.0023	.0040	.0007	.0012	.0035	.0005
Tractor, fill & unload	.0036	.0036	.0036	.0036	.0036	.0036
Labor to:						
Fill bin	.0118	.0118	.0118	.0118	.0118	.0118
Unload bin	.0059	.0059	.0059	.0059	.0059	.0059
Check progress	.0090	.0161	.0032	.0048	.0138	.0024
Prepare bin	.0052	.0052	.0052	.0048	.0048	.0048
Total cost/bu	$.0537	.1133	.1143	.0405	.0676	.0720
24-ft diam bin with 9-hp fan:						
LP gas	$----	.0395	.0788	-----	-----	.0395
Fan operation	.0150	.0261	.0048	.0080	.0231	.0033
Stirring	.0017	.0029	.0005	.0009	.0026	.0005
Tractor, fill & unload	.0018	.0018	.0018	.0018	.0018	.0018
Labor to:						
Fill bin	.0059	.0059	.0059	.0059	.0059	.0059
Unload bin	.0029	.0029	.0029	.0029	.0029	.0029
Check progress	.0066	.0118	.0024	.0035	.0101	.0018
Prepare bin	.0038	.0038	.0038	.0035	.0035	.0035
Total cost/bu	$.0377	.0947	.1011	.0266	.0499	.0592
27-ft diam bin with 9-hp fan:						
LP gas	$----	.0395	.0788	-----	-----	.0395
Fan operation	.0126	.0218	.0040	.0067	.0192	.0027
Stirring	.0014	.0024	.0004	.0007	.0021	.0003
Tractor, fill & unload	.0018	.0018	.0018	.0018	.0018	.0018
Labor to:						
Fill bin	.0059	.0059	.0059	.0059	.0059	.0059
Unload bin	.0029	.0029	.0029	.0029	.0029	.0029
Check progress	.0055	.0099	.0020	.0029	.0084	.0015
Prepare bin	.0032	.0032	.0032	.0029	.0029	.0029
Total cost/bu	$.0333	.0874	.0990	.0239	.0433	.0576

* Supplemental heat required to dry to 19%, unheated natural air used to finish drying to 13.5%.

Table 3. Continued. Variable costs per bushel for drying wheat with various drying systems, starting at 25% or 19% moisture content.

Component	To dry from 25 to 13.5%			To dry from 19 to 13.5%		
	Solar	LP gas + air only*	LP gas	Solar	Unheated air only	LP gas
30-ft diam bin with 13-hp fan:						
LP gas	$----	.0395	.0788	-----	-----	.0395
Fan operation	.0142	.0246	.0046	.0075	.0217	.0031
Stirring	.0016	.0028	.0004	.0009	.0025	.0004
Tractor, fill & unload	.0018	.0018	.0018	.0018	.0018	.0018
Labor to:						
Fill bin	.0059	.0059	.0059	.0059	.0059	.0059
Unload bin	.0029	.0029	.0029	.0029	.0029	.0029
Check progress	.0043	.0077	.0015	.0023	.0066	.0011
Prepare bin	.0025	.0025	.0025	.0023	.0023	.0023
Total cost/bu	$.0332	.0877	.0984	.0236	.0437	.0570

* Supplemental heat required to dry to 19%, unheated natural air used to finish drying to 13.5%.

Table 4. Fixed plus variable costs per bushel for drying wheat.

Situation considered	To dry from 25 to 13.5%			To dry from 19 to 13.5%		
	Solar	LP gas + air only*	LP gas	Solar	Unheated air only	LP gas
18-ft diam bin with 7-hp fan:						
Purchase entire system $	.87	1.05	1.04	.82	.85	.94
Storage bin available	.46	.62	.61	.42	.45	.54
Aeration bin available	.39	.55	.55	.35	.39	.48
Sys. on hand w/o stirrer	.25	.31	.30	.22	.25	.25
Sys. on hand w/stirrer	.06	.13	.12	.05	.08	.08
21-ft diam bin with 7-hp fan:						
Purchase entire system $	.78	.92	.92	.71	.74	.82
Storage bin available	.47	.58	.58	.42	.45	.51
Aeration bin available	.29	.45	.45	.26	.29	.38
Sys. on hand w/o stirrer	.20	.26	.26	.17	.20	.21
Sys. on hand w/stirrer	.05	.11	.11	.04	.07	.07
24-ft diam bin with 9-hp fan:						
Purchase entire system $	.66	.78	.78	.61	.63	.70
Storage bin available	.32	.44	.44	.29	.31	.38
Aeration bin available	.27	.39	.40	.25	.27	.34
Sys. on hand w/o stirrer	.19	.25	.25	.17	.19	.20
Sys. on hand w/stirrer	.04	.09	.10	.03	.05	.06
27-ft diam bin with 9-hp fan:						
Purchase entire system $	.64	.74	.75	.59	.60	.67
Storage bin available	.29	.39	.40	.26	.28	.34
Aeration bin available	.24	.34	.35	.21	.23	.29
Sys. on hand w/o stirrer	.16	.22	.23	.15	.17	.18
Sys. on hand w/stirrer	.03	.09	.10	.02	.04	.06
30-ft diam bin with 13-hp fan:						
Purchase entire system $	.57	.66	.67	.52	.54	.59
Storage bin available	.27	.36	.38	.25	.27	.32
Aeration bin available	.23	.32	.33	.21	.23	.28
Sys. on hand w/o stirrer	.15	.20	.21	.13	.15	.17
Sys on hand w/stirrer	.03	.09	.10	.02	.04	.06

* Supplemental heat required to 19%, unheated natural air used to finish drying to 13.5%.

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