Solar Grain Drying: Progress and Potential

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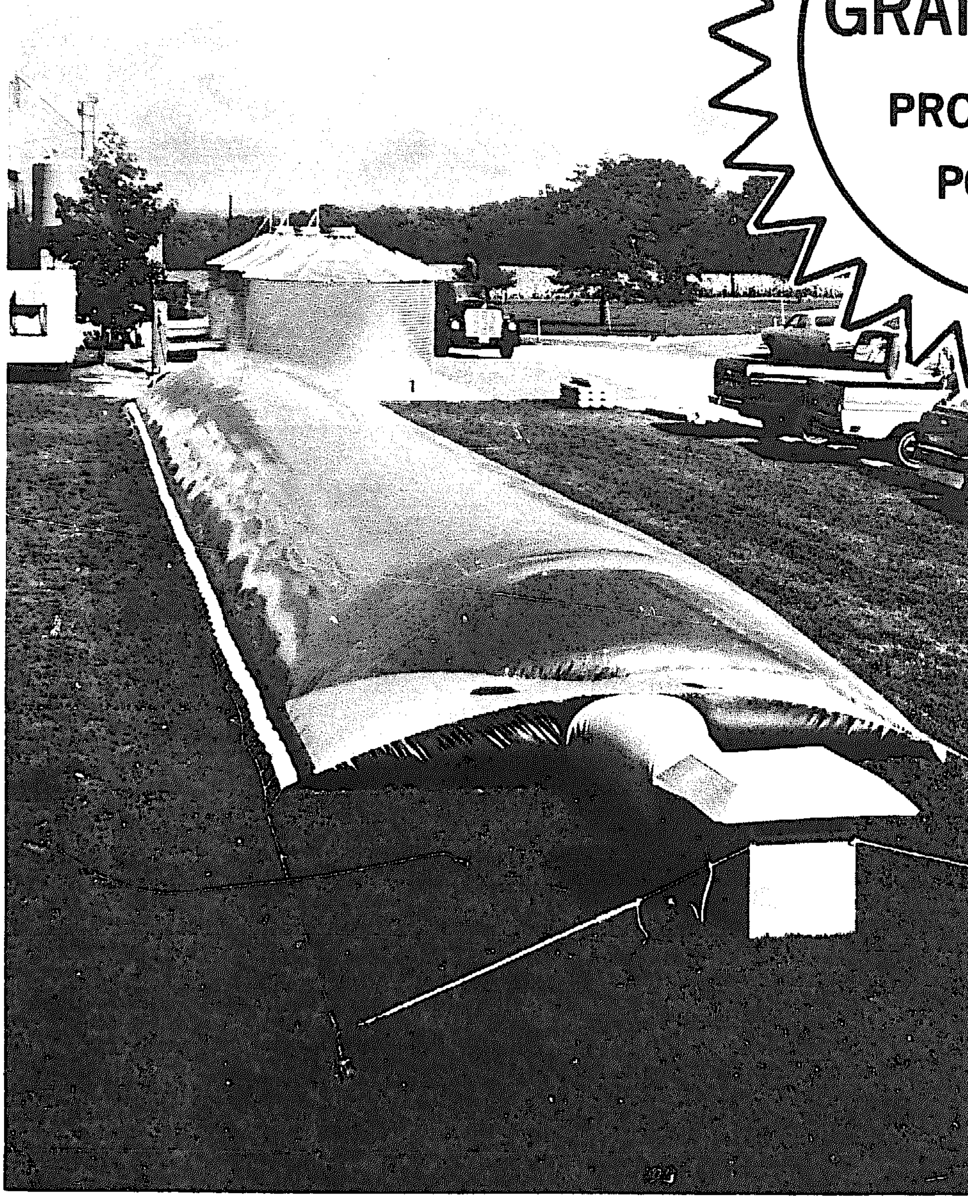
PROGRESS AND POTENTIAL



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ABSTRACT

Drying grain, especially corn, with conventional artificial drying methods requires great quantities of petroleum fuel during a short harvest period. Two systems of drying are used: high-speed, high-temperature batch or continuous-flow and low temperature in-storage drying. Solar energy was studied as an alternative or supplemental energy source for low-temperature drying at several different Midwest locations.

Adoption of solar grain drying depends on supply and price of petroleum fuel and on competition for scarce fuel for other agricultural uses such as powering field operations and manufacturing fertilizer.

Key words: Grain drying, solar energy, low-temperature drying, heat storage, supplemental solar heat, high-temperature drying, solar collectors, radiant energy, computer simulation.

PREFACE

This publication reports research in progress and assesses the state of the art of solar grain drying. It is directed toward investigators interested in applying solar energy, to agriculturists concerned with applied technology, to manufacturers and merchandizers of drying equipment—solar and conventional—and to potential users of solar grain drying on farms or wherever crops are dried.

Some solar grain drying research has been in progress since the 1950's (*1*) (*4*) (*8*) (*14*) (*15*) (*19*). However, the increased emphasis placed on solar drying in response to the 1973 fuel crisis and the resulting effort toward U.S. energy self-sufficiency sparked renewed efforts in direct application of solar energy to meet agricultural energy needs. Funding initiated by the National Science Foundation in late 1974 and assumed by the U.S. Engery Research and Development Administration (ERDA) in January 1975 has been responsible for much of the renewed research effort. Research on the application of solar energy to agriculture is managed for ERDA by the Agricultural Research Service (ARS) in cooperation with the Cooperative States Research Service, U. S. Department of Agriculture. Some of the funds have been used to expand ARS research in solar grain drying, but most of the money has been distributed to State agricultural experiment stations and other research agencies through research agreements and contracts.

Proof of concept tests started late in 1974 included research at two ARS locations and seven State agricultural experiment stations. The station locations and the investigators in charge include:

University of Illinois, Urbana, Gene C. Shove
Iowa State University, Ames, Carl J. Bern
Kansas State University, Manhattan, Ralph I. Lipper
University of Minnesota, St. Paul, R. Vance Morey
Ohio Agricultural R&D Center, Wooster, Harold M. Keener
Purdue University, W. Lafayette, Ind., Robert M. Peart
South Dakota State Univ., Brookings, Mylo A. Hellickson
ARS, Iowa State University, Ames, Gerald L. Kline
ARS, U.S. Grain Marketing Research Center, Manhattan, Kans., George H. Foster

Early in 1975, a computer simulation program was initiated to determine at what locations and under what weather and crop conditions solar grain drying shows the most promise. In addition to some of the institutions already listed, simulation work at the University of Nebraska was inaugurated under the leadership of T. L. Thompson. Also funded at the same time was field testing of solar rice drying by ARS at the Texas A&M University Research & Extension Center at Beaumont with D. L. Calderwood, investigator.

Later in 1975 three experiment stations, one additional ARS location, and a research and consulting firm were added to the program. The locations and the lead investigators include:

Colorado State University, Ft. Collins, Ralph Hansen
Michigan State University, E. Lansing, F. W. Bakker-Arkema
University of Missouri, Columbia, D. B. Brooker
ARS, Purdue University, Lafayette, Ind., John R. Barrett
Helio Associates, Inc., Tucson, Ariz., A. B. Meinel.

Technical papers have been developed on some of the individual projects. The papers have been presented at professional meetings or published in scientific and trade journals. These are listed in References *6*, *12*, *13*, *16*, *17*, *18* and *20*, page 14.

Conversion table—English to metric units

To convert from	To	Multiply by
Foot^2	Meter^2	.0929
Mile^2	Kilometer^2	2.590
Acre	Hectare	.4047
British thermal unit	Joule	1055
Btu/ft^2-hr	Watt/meter^2	3.152
Foot	Meter	.3048
Horsepower	Watt	745.6
Foot^3	Meter^3	.0283
Gallon	Liter	3.785
Bushels	Tonne	.0263
Btu/ft^2—hr, day, etc.	kWh/meter^2—hr, etc.	.00315
Btu/ft^2-day	Langley/day	.2710
Cfm/bu	Meter^3/min-tonne	1.075

CONTENTS

bean-growing area where certain disease problems develop in the field, requiring early harvest followed by artificial drying.

The growing practice of double-cropping frequently requires artificial drying of the crops to make the system work. Wheat and barley are grown ahead of cotton in the Southwest and soybeans follow wheat in the Midwest.

SOLAR ENERGY—AVAILABILITY AND HISTORY

Background

Crops convert and store solar energy by photosynthesis. Estimates (21) are that energy equivalent to 300 million tons (273×10^6 tonnes) of coal is fixed through photosynthesis each year, an amount equal to about one-seventh of the total energy used annually in the United States. For the other six-sevenths of the energy used, the United States depends on the results from photosynthesis that took place in past ages. Coal has been called black sunshine because it is the result of preserved plant material. Oil is called liquid sunshine because it comes largely from deposits of animal life that ate the plant life that fixed energy from the sun. Obviously solar energy has been used almost exclusively to power the economy—and it continues to do so. However, the reserves that have been accumulated and stored in the form of coal and petroleum are disappearing rapidly.

Unfortunately, photosynthesis is not an efficient process, and little of the total energy from the sun falling on the earth's surface is converted into plant material. Corn utilizes solar energy through photosynthesis more efficiently than most other crops. Yet the grain harvested from an acre of corn represents energy equal to only about 1 percent of the solar energy available over the growing season. Estimates (23) show that by collecting and using all of the solar energy available, the total U.S. energy requirement could be met on 4,300 square miles (11,137 km²) or 0.1 percent of the land area in the United States. So why not collect this energy directly and use it more efficiently to meet energy needs?

Solar energy has been applied directly in agriculture for many years. The sun and the wind dry mature crops standing in the fields, in the stack or windrow, or in a ventilated shed or crib. Efforts to collect and concentrate solar energy directly extend back 2,000 years or more. However, considerable investment in equipment is required to collect solar energy in amounts sufficient to replace significant quantities of fossil fuel. A few facts on solar energy availability will document this.

Solar energy availability

Although the total energy from the sun is immense, it is diffuse and often needs to be concentrated to be used effectively. Solar energy is also intermittent both on a daily basis and on a day-to-day basis, depending on the amount of cloud cover. The energy received from the sun just outside the earth's atmosphere (the solar constant) is about 430 Btu/ft²-hr (1,355 W/m²) (3). At the earth's surface, 290 Btu/ft²-hr (914 W/m²) is received on a surface normal to the sun. However, averaged over day and night, cloudy and bright, solar energy received on a horizontal surface in the United States is about 65 Btu/ft²-hr (205 W/m²) or 1,560 Btu/ft²-day (4.9 kWh/m²-day). Further, this ranges from 2,000 Btu/ft²-day (6.3 kWh/m²-day) in the desert southwest to about 1,300 Btu/ft²-day (4.1 kWh/m²-day) in the central Corn Belt (7).

The seasonal variation in solar energy must be considered in determining the amount of solar energy available for grain drying. As indicated in figure 1, solar energy available on a horizontal surface peaks in June and July, but most of the drying requirements are for fall maturing crops harvested in September through November. At 40° north latitude (central U.S. Corn Belt), the solar

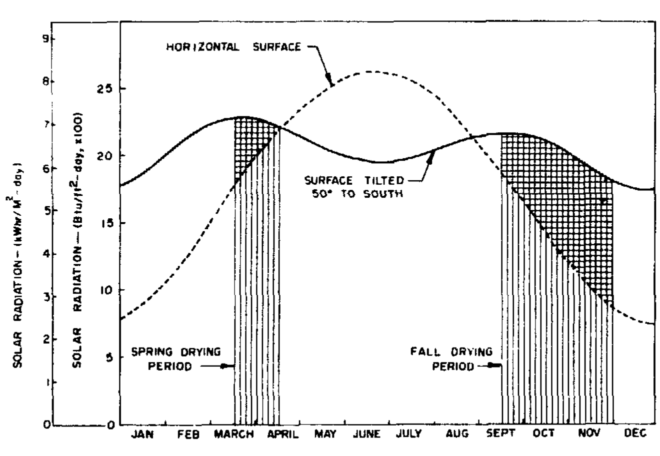

Figure 1.—Effect of tilting collector surface to south 50° above horizontal on the radiation received during the fall and spring drying seasons in the central Corn Belt.

SOLAR GRAIN DRYING

PROGRESS AND POTENTIAL

George H. Foster and Robert M. Peart[1]

INTRODUCTION

Grain drying is an energy intensive agricultural operation that will be increasingly affected by the growing fossil fuel shortage. Of the crops requiring drying, corn uses the most energy. It is the largest grain crop in terms of total production and is normally harvested with more excess moisture than any other grain crop. Corn matures in the fall and is subject to extensive field losses if not harvested before winter. Corn harvest is normally concentrated in a few weeks in the fall. Thus, not only is the requirement for energy great, but this demand is concentrated during a short period.

Energy required for drying corn often exceeds the total amount required for preparing the seedbed, planting, cultivating, and harvesting the crop. Recent estimates (*11*)[2] of energy requirements for drying corn are 56×10^{12} Btu (59.1×10^{12} kJ), and for rice, 3×10^{12} Btu (3.2×10^{12} kJ). The fuel equivalent is about 640 million gallons (2.4×10^9 liter) of LP gas.

Liquified petroleum (LP) and natural gas are the principal fuels used for drying. Some fuel oil is used in the larger, nonfarm installations. Electricity use is increasing for low temperature drying on farms.

One approach to drying grain involves a high speed, usually high temperature operation, where the grain is held in batches or is passed continuously through a special container. The dryer is designed for optimum exposure of the grain to the drying air and for easy movement of the grain into and out of the drying chamber. From 90 to 95 percent of the energy used in high-speed dryers is supplied by fossil fuels.

Another drying process, usually referred to as low-temperature drying, takes place over an extended period while the grain is held in the storage bin. According to recent data from the Corn Belt (2), about one-fifth of the corn is now dried by low-temperature, in-storage drying systems. This system maximizes the use of heat in natural air; solar energy as a source of supplement heat was first used with this method of drying.

Rice normally requires drying after harvesting. Most of the crop is dried at commercial drying installations or at rice mills in continuous-flow, heated-air dryers by the multipass method, but a considerable part of the crop in the three production areas in the United States is dried on the farm in storage bins. Because of new acreage planted to rice in the Arkansas-Mississippi area during the past 2 years and commercial facilities being slow to respond to the increased production, there has been a large increase in on-farm drying in this area. Commercial dryers in California use a combination system in which rice is dried to 16 to 18 percent moisture in a continuous-flow, heated-air dryer, then drying is finished with ambient air while the rice is in storage.

The other grain crops require drying occasionally. Grain sorghum is normally grown in the drier regions of the United States, but some of it is dried in nearly all production areas. Wheat requires drying somewhere in the wheat-producing area almost every year. The moisture that must be removed from wheat is small compared to corn and rice, and the drying usually can be done with natural air. Soybeans, an oilseed crop, do not require drying every year. When the crop does need drying, the amount of moisture removed is small. Exceptions occur in more humid parts of the soy-

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[1] Agricultural engineer, U.S. Grain Marketing Research Center, Agricultural Research Service, Manhattan, Kans., and professor of agricultural engineering, Purdue University, West Lafayette, Ind.

[2] Italic numbers in parentheses refers to References, page 14.

radiation falling on a horizontal surface on October 21 is just about half that falling on the same surface on June 21. However, by tilting the solar collector to the south so that it is normal to the noonday sun, this difference is smaller. The direct radiation normal to the sun on October 21 is 2,454 Btu/ft^2-day (7.7 kWh/m^2-day) compared to 3,180 Btu/ft^2-day (10.0 kWh/m^2-day) in June. For the most part, this difference in available solar energy is due to the change in day length from October to June.

On a clear day at 40° north latitude, 2,648 Btu/ft^2-day (8.4 kWh/m^2-day) is received on a horizontal surface on June 21, but only 610 Btu/ft^2-day (1.9 kWh/m^2-day) on a vertical surface (3). On October 21, 1,348 Btu/ft^2-day (4.2 kWh/m^2-day) is received on a horizontal surface and 1,654 Btu/ft^2-day (5.2 kWh/m^2-day) on a vertical surface. From the middle of October through the middle of March, more energy can be collected on a vertical surface than on a horizontal surface at this latitude. By tilting the collector optimally to the south during the fall drying season—an angle of about 50° with the horizontal in the Corn Belt area—nearly 2,100 Btu/ft^2-day (6.6 kWh/m^2-day) will be received on clear days. By going one step further and making a tracking collector that will follow the sun from sunrise to sunset, the amount received will increase to 2,450 Btu/ft^2-day (7.7 kWh/m^2-day).

The foregoing discussion gives some idea of the solar energy available on an annual average basis and how this varies by geographical location, by time of the year, and by orientation of the collector. Still to be dealt with is the matter of the intermittent nature of the availability of solar energy. In the first place, it is only available for 8 to 14 hours each day. The daily fluctuations in solar energy availability is perhaps easier to accommodate than the situation where sun energy may not be available at all, or is available at low levels, during cloudy or rainy weather. A constant source of energy is not available unless there is some means of storing excess energy during sunny weather. The probabilities of receiving various levels of solar radiation have been calculated for the North Central region of the United States, and other locations (5) (7).

SOLAR ENERGY—DRYING GRAIN

Solar energy is considered more applicable to low-temperature, in-storage drying systems than to high-temperature, high-speed systems. In-storage drying systems require low levels of heat input over extended periods. Such drying methods tolerate intermittent or variable levels of heat input.

In most areas of the Corn Belt, the relative humidity of the outdoor air during sunny weather is low enough to dry corn to the desired moisture level without added heat. When solar heat is added in the daytime, continued fan operation during the night when the relative humidity is high helps offset daytime overdrying and provides more uniform drying through the total grain depth. The overdried grain picks up moisture from the high humidity night air. This reduces overdrying and lowers the air humidity so the grain above the overdried layer will continue to dry. However, there is insufficient energy stored in the overdried grain to permit drying to proceed during long periods of inclement weather.

Low-temperature drying is weather dependent and may be least successful during the years when it is needed most—years when the crops mature late or when field drying conditions are poor. Insolation levels (the amount of incoming solar radiation) are usually low when field drying conditions are poor. In some areas backup heat systems are necessary. This limits the attractiveness of solar energy because the cost of collecting solar energy must be offset entirely by savings in fuel cost. Where the solar heating system replaces other heating systems, the cost of the solar collector is partially offset by the cost of the heating equipment replaced.

The feasibility of applying solar energy to high-speed batch and continuous flow drying systems has not been established. Where the amount of moisture to be removed is relatively low, as in the case with wheat or soybeans, higher speed solar drying systems employing batch-in-bin drying methods are feasible. This has been demonstrated in solar drying tests with soybeans in Ohio (16).

Successful application of solar energy to high-temperature, high-speed, batch or continuous flow-drying systems presents several problems. Costs of collector systems to provide high temperatures (120° to 180°F or 49° to 82°C) are considerably greater than for lower temperature systems. Collection efficiencies are reduced in high-temperature collectors unless expensive measures are taken to limit heat losses.

To supply the quantity of heat normally used in high-speed, high-temperature dryers, extensive areas for deploying the solar collectors are needed. Heating capacity of these dryers ranges from 2 to 10 million Btu/hr (2.1 to 10.6 $\times$ 10^6 kJ/hr) and higher, depending upon the hourly drying capacity. At a collection efficiency of 50 percent, collectors covering nearly 2 acres (0.81 hectares) would be needed to provide 5 million Btu/hr (5.3 $\times$ 10^6 kJ/hr).

SOLAR COLLECTORS AND COLLECTION EFFICIENCIES

General

A simple solar collector is made up of radiant energy transmitting material and an energy absorbing material in a frame or enclosure. The transmitting material usually serves as the cover or enclosure. Conventional, flat-plate collectors are shown schematically in figure 2. The cover or glazing is usually glass or clear plastic. The absorber for air heating collectors may be metal, wood, paper, or plastic, but performs best if it is slightly rough and has a dull, black finish. The back of the collector and sometimes the sides are insulated to prevent heat losses. In some cases, a bare-plate collector with no cover is used.

The absorber may be corrugated or V-shaped to

PN-5189

Figure 3.—Commercially available inflated plastic solar collectors used in tests at Purdue University.

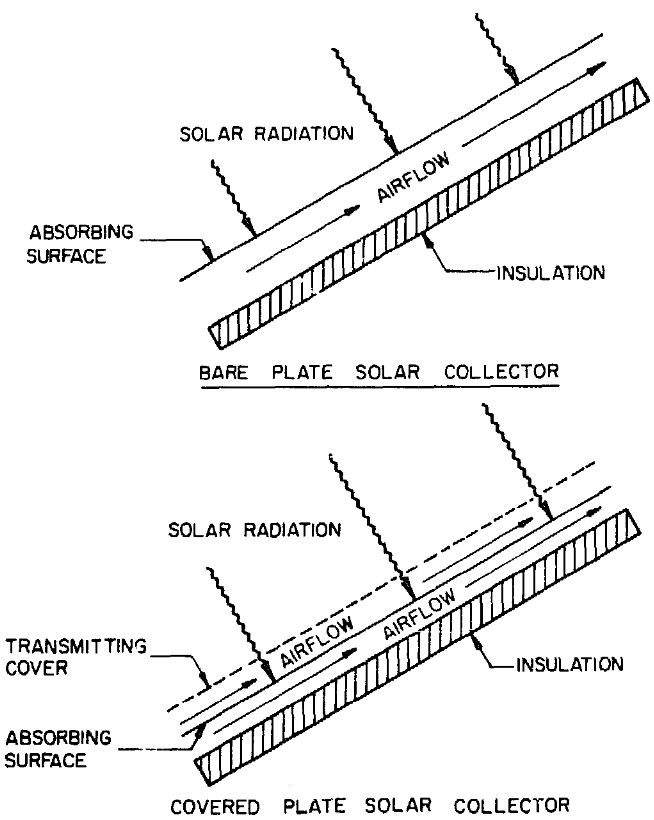

Figure 2.—Schematic of bare-plate and covered-plate solar collector for heating air.

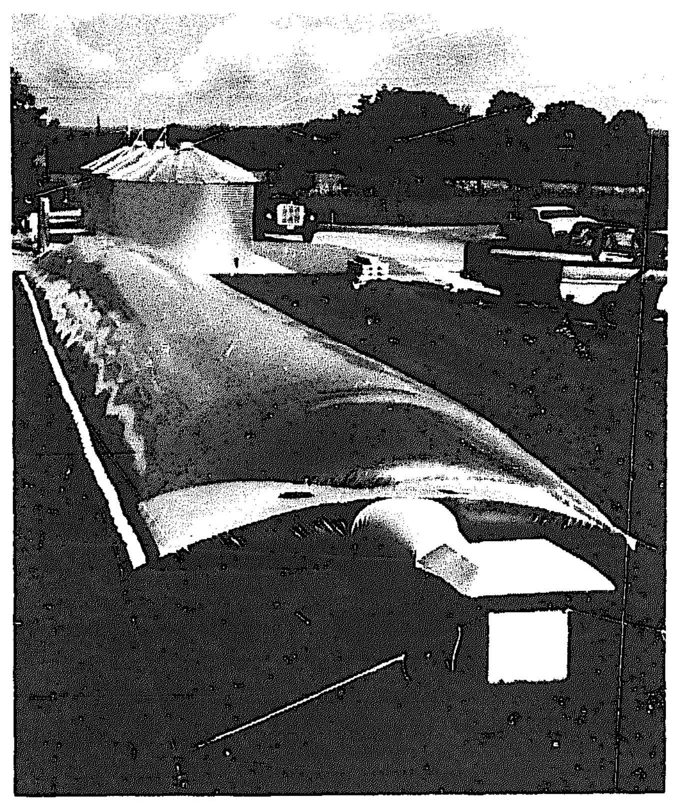

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Figure 4.—Inflated plastic collector used in solar drying tests at the Ohio Agricultural Research and Development Center.

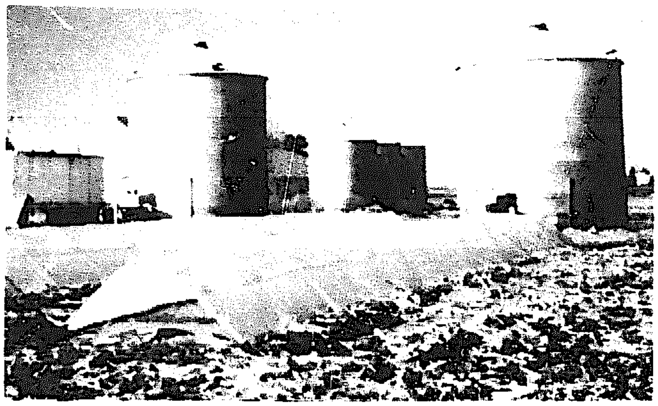

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Figure 5.—Commercially available solar collector made of plastic film supported by a wire frame.

help trap the incoming solar radiation. The cover should transmit a high percentage of the short wave radiation from the sun. Glass and some plastic materials transmit 90 percent of the sun's energy. The cover, in addition to transmitting solar radiation, serves to reduce heat loss caused by wind convection and from emission of long wave radiation from the absorber. In some cases, two or more layers of cover material are used.

In an air-heating collector, the air is drawn or forced on one or both sides of the absorber. Heat is transferred from the absorber to the air moving over it. In a liquid heating solar collector, fluid is circulated through channels formed in the absorber or through pipes attached to it. The absorber in liquid systems is usually made of metal to increase the heat transfer from the absorber to the fluid.

Solar collectors used for grain drying

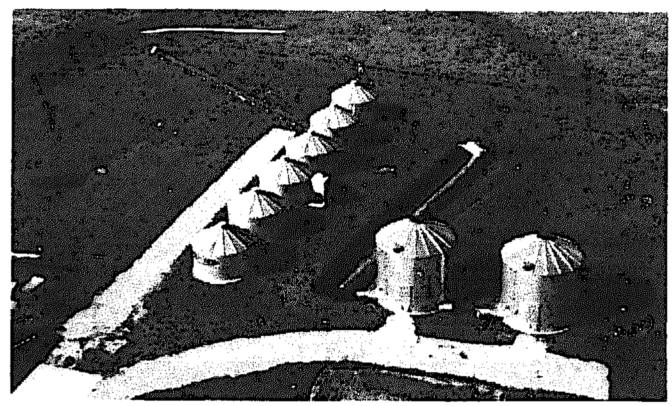
Plastic collectors either air inflated or supported on a light frame are now available commercially for drying grain. One, a clear, quonset-shaped (hemicylinder) polyvinyl plastic film enclosure, provides about 1,000 ft^2 (93 m^2) of collection area (figs. 3 & 4). Inside the clear plastic is a black plastic absorber, also inflated. A separate electrically driven fan is used to inflate the collector and deliver solar-heated air to the intake of the fan on the drying bin.

Another plastic collector has a clear polyethylene cover over a triangular, wire frame with the black polyethylene film absorbing surface forming the floor (fig. 5). Air is drawn through the collector and heated on its way to the fan on the drying bin.

A third plastic collector employs two inflated tubes: a black absorber tube inside a slightly larger diameter clear plastic tube (fig. 6). The tubes are inflated either by placing the drying fan at the end farthest from the bin or by a separate fan that delivers air through the collector to the intake of the drying fan on the bin.

The cost of materials for the tube-type solar collectors used at the U.S. Grain Marketing Research Center was quite low. Polyethylene plastic (6 mil (.15 mm) thickness) that made up the double-tube collectors cost about 30 cents/ft^2 (\$3.23/m^2) of net collector area. Tape for the seams to make tubes from flat sheets plus the straps used for attachment at each end added another 3 to 5 cents/ft^2 (32 to 54 cents/m^2). This simple collector was fabricated from materials available from a local retail building supplier. Two men made the tubes in 3 or 4 hours. Some additional time was required to make the metal transitions or connections between the fan and the tube and between the tube and the bin.

A flat-plate collector through which the drying air was drawn into the drying fan on the bin was



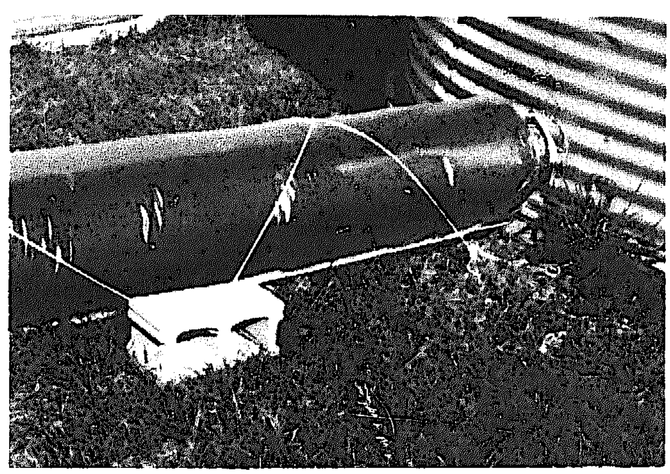


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Figure 6.—General overhead view (above) and closeup (below) of the tubular collectors used at the U.S. Grain Marketing Research Center, Manhattan, Kans.

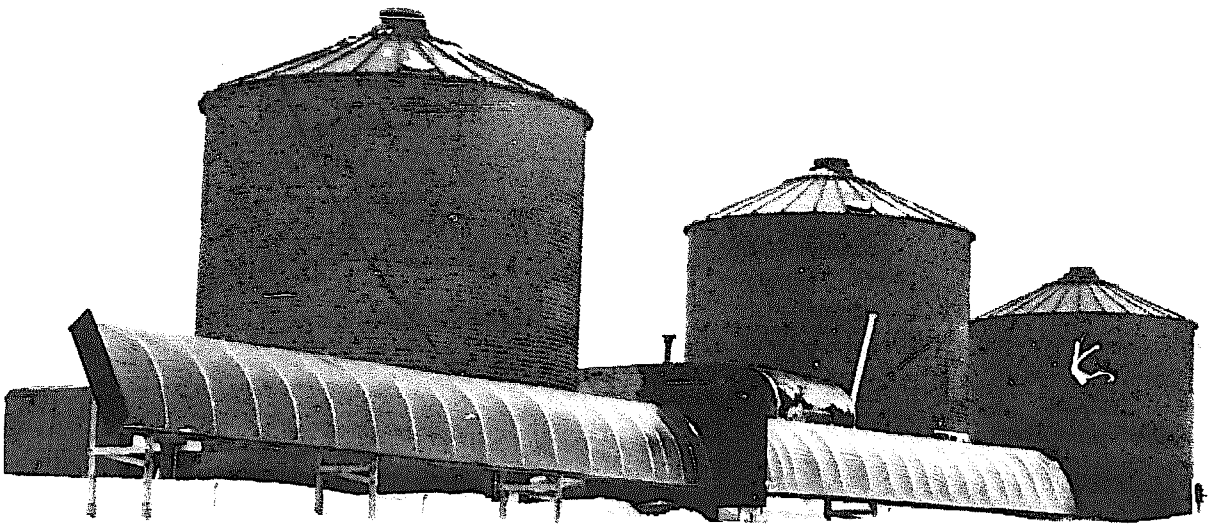

Figure 7.—Flat-plate collector used in Iowa tests. PN-5194

tested in Iowa. The collector was tilted optimally toward the sun and had a cover of clear polyethylene plastic film held in position with bowed wood slats or welded wire mesh (fig. 7). The cost of the materials for the 250 ft^2 (23.2 m^2) shop-built collector was $150.

The thickness of the plastic film used with the different collectors varied from 4 to 10 mil (.1 to .25 mm).

Another approach to collecting solar energy for drying grain has been to build the collector into the drying and storage bin. Early tests in South Dakota used a collector wrapped around the circumference of a round bin, except for the one-third facing the north (fig. 8). Similar approaches were used in Illinois (fig. 9). Air was drawn between the

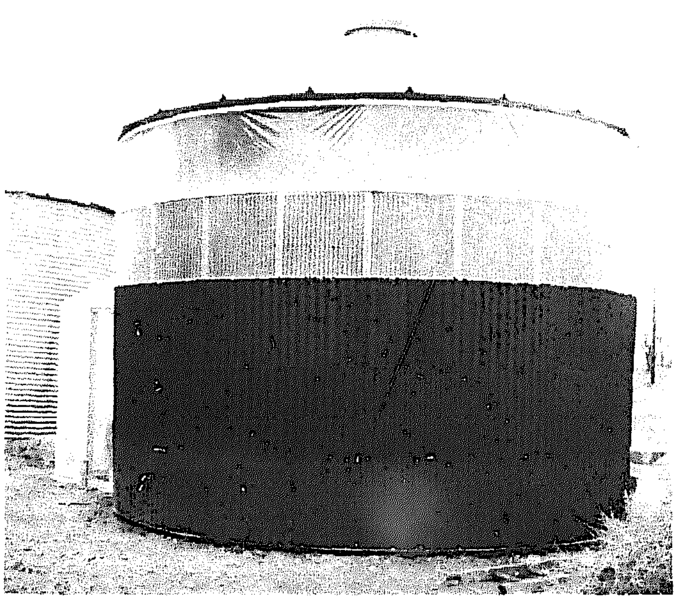

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Figure 8.—Solar collectors of different types and materials mounted on circular bin for tests in South Dakota.

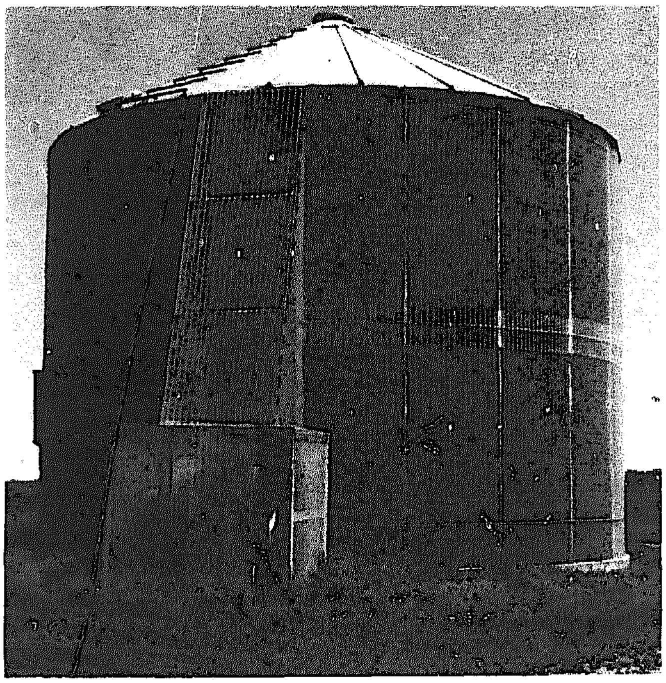

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Figure 9.—Bin wall collector tested in Illinois was made of clear corrugated fiberglass over a black painted wall.

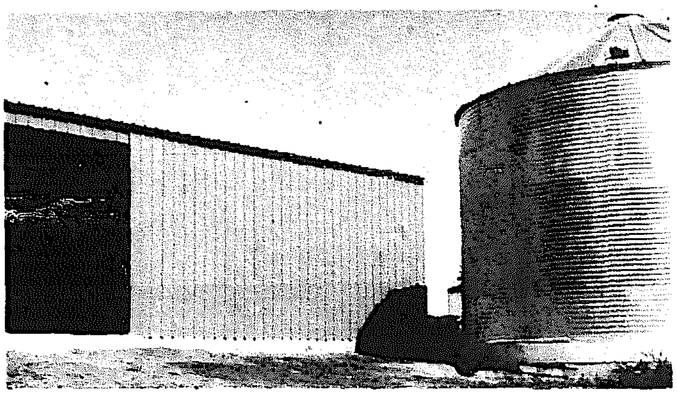

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Figure 10.—The roof of this machinery shed in Wisconsin was made into a solar collector and used to warm air for drying corn in the adjacent bin.

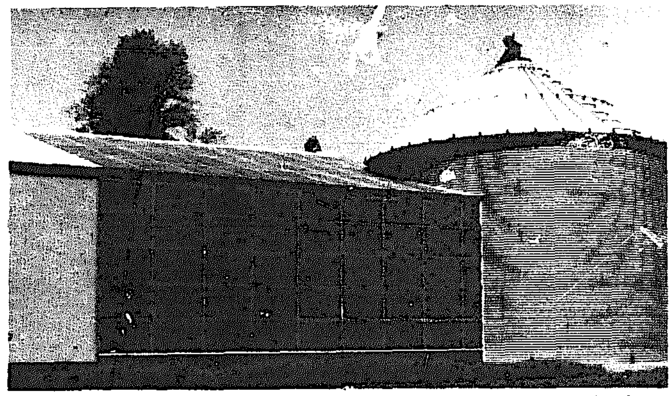

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Figure 11.—Solar collector with clear fiberglass cover built into wall and roof of Illinois machinery storage.

collector surface and the bin wall and into the drying fan.

Also in Illinois and Wisconsin, the roof or sidewall, or both, of adjacent metal storage structures, usually machinery sheds, were made into bare-plate solar collectors. Air was pulled through these collectors and ducted to a fan on the nearby drying bin (fig. 10). A radiant energy transmitting exterior wall, usually corrugated fiberglass panels, was used in newly constructed livestock shelters and machinery storages to provide covered-plate solar collectors for grain drying and for other uses (fig. 11).

The size of the collectors used for low-temperature grain drying ranged from 0.10 to 0.75 ft^2/bu (0.35 to 2.65 m^2/tonne)[3] of grain dried. In the batch-in-bin system, from 4 to 8 ft^2 of collector area was used for each bushel (14 to 28 m^2/tonne) of grain.

Temperature rise in the drying air from the solar collectors depends largely on the size of the collector, the insolation rate, and the volume of air heated, along with the other factors affecting collector efficiency (9). As used in most of the tests with in-storage drying systems, the collectors heated the air a maximum of 5° to 30°F (2.8° to 16.7°C) at noon on a clear sunny day. (The solar heated air was sometimes mixed with larger quantities of outdoor air, thus reducing the effective drying air temperature.) The average temperature rise for the test period including day and night, cloudy and bright, varied from 1° to 6°F (0.55° to 3.3°C). A typical sunny day pattern of temperature increases from solar and from fan energy in one drying test is shown in figure 12.

At the U.S. Grain Marketing Research Center, the amount of solar energy collected in eight tests averaged 620 Btu/ft^2-day (2.0 kWh/m^2-day). Thus, each 100 ft^2 (9.3 m^2) of collector provided energy equal to 18.6 kWh of electricity or about 0.67 gallon of LP gas each day.

Collector Efficiency

Factors affecting collector efficiency are numerous. Some of the more important ones are discussed briefly. Already mentioned was the advantage of

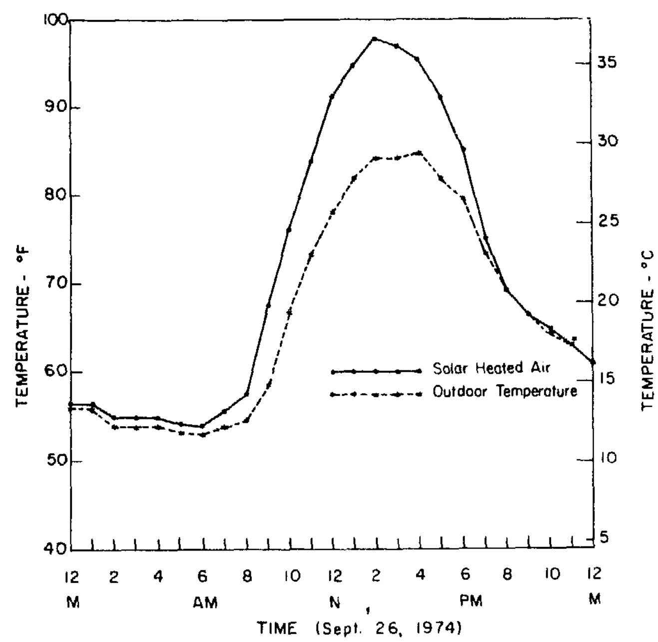


Figure 12.—Typical sunny day temperatures in drying tests with solar heat.

[3] Because of the different grains and bushel weights involved, all conversion from bushel to metric tons was arbitrarily made on the basis of 38 bu/tonne.

tilting flat-plate collectors toward the south during the fall and winter months. Also, a collector positioned vertically collects more solar energy than one positioned horizontally from November through February.

The tubular collector, although stationary, has some of the characteristics of a tracking collector. When oriented north and south, it presents approximately the same optical cross section to the sun from sunrise to sunset. However, as the sun "moves south" after the fall equinox, more energy will be collected by a tubular collector oriented in an east-west direction. When the midday sun strikes the collector surface at an angle of 40° or less, most of the energy is reflected (*10*). With the cylindrical collector oriented east and west, the cross section of the collector that is normal to the sun when it is low in the southern sky is the same as when the sun is overhead. In tests conducted in Ohio with the quonset-shaped collector in November, the east-west collector consistently produced higher maximum temperature rises and higher heat outputs than the north-south collector.

The temperature at which the solar collector operates has a direct effect on collection efficiency: the higher the temperature in the collector, the greater the heat loss. In the tubular collectors tested, about half of the air temperature rise occurred in the first 40 feet (12.2 m) of a 100-foot (30.5 m) long collector. Little temperature change occurred in the last 20 feet (6.1 m) of the collector since the losses from that point were about equal to the energy collected. The losses from the tube also increased as the wind speed increased.

Performance of uninsulated collectors installed on the ground depends on the amount of heat stored in the soil underneath the collectors. During hot sunny weather, the ground underneath the collector is warmed. The heat thus stored in the ground warms the air when no solar energy is available. In Ohio tests conducted in the fall, heat storage in the soil was found to increase overall collection efficiency enough so the uninsulated collector supplied about 25 percent more energy than a similar collector insulated from the ground.

The collection efficiency reported for the various low-temperature collectors used in the grain drying tests ranged from 12 to 62 percent. The collectors that showed an efficiency of 62 percent over an entire test period were small diameter, cylinders or tubes. The lower collection efficiencies reported were from unpainted, bare-metal collectors mounted on the sidewalls of bins.

Collection efficiencies were calculated from the quantity of heat collected per unit area expressed as a percentage of the solar energy available, usually on a horizontal surface, either as reported by the former U.S. Weather Bureau or as collected at the test site with Weather Bureau type instruments and procedures. In Iowa, solar pyranometers were mounted to provide a measure of the solar energy available on the tilted surface of the collectors used. When proper corrections are made for collector orientation, sun angles, and other factors affecting collector performance, the collection efficiency of low-temperature, uninsulated, solar collectors without heat storage is in the 30 to 50 percent range.

Solar energy may be used directly when it is available or may be stored to be used later during the night or during periods of rainy or cloudy weather. Air heated with solar energy can be used to heat pebbles or rocks during sunny weather. The drying air is then moved through the rocks during the night to recover the stored heat and to lower the humidity of the drying air.

A collector unit containing a rock heat storage was built and tested at the U.S. Grain Marketing Research Center late in the 1975 drying season (fig. 13). The collector covered an area of about 300 ft^2 (28 m^2) and contained 30 tons (27.3 tonnes) of rocks as the storage medium. Air pulled continually through the collector-storage system on a typical sunny day reached maximum temperatures about 7 p.m. and remained above ambient temperature until about 9 a.m. the following day. During the best sunshine hours, 9 a.m. to 4 p.m., the rocks were being reheated, and the temperature of air pulled through the rock bed was below ambient. Thus, the collector-storage system was supplying the most heat during the night when the humidity was high and the least during the day when the air was normally dry.

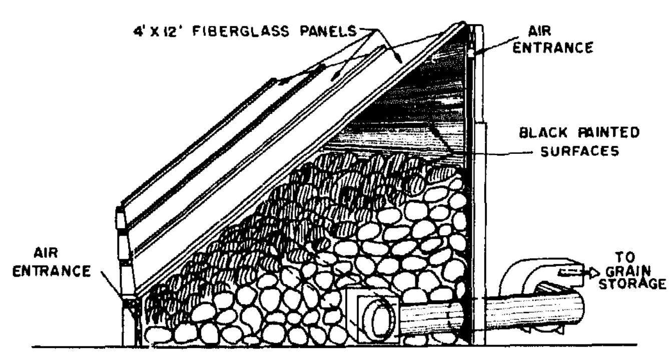


Figure 13.—Half-section perspective of solar collector with rock-pile heat storage.

Other important factors in collector performance are reliability and expected life. Plastic collectors are subject to damage from wind, ice, and snow, as well as damage from rodents, farm animals, domestic pets, and vandals. Air-inflated, plastic collectors have been relatively free from wind damage while inflated. Rodent and other animal damage is also minimal when the collectors are inflated. When collectors are deflated and lying on the ground, livestock or machinery passing over them may punch holes in the plastic, and dogs may tear the plastic when trying to get at mice under the collectors. Thus, they should be stored when not in use.

Wet snow has caused the larger, half-cylinder or quonset-shaped collectors to collapse. The clear, vinyl plastic covers become quite brittle during cold weather and shatter if struck or deformed. Fortunately, much of the damage to the plastic collectors can be repaired easily with mending tape. Many plastic collectors are still serviceable after 2 years.

The bare-metal collectors used on the sides of bins are not easily damaged when anchored properly to withstand strong winds. Surfaces may need to be recoated with flat, black paint to absorb maximum amounts of solar radiation. Weathered, galvanized metal has proved to be a reasonably effective collecting surface, and painting of bare-metal collectors may not always be important.

Unshaded areas to deploy solar collectors are often limited. Some compromise in efficient, grain-handling principles may be required to accommodate multiple bin arrangements that utilize solar energy for drying. Although bin-mounted collectors take up minimum ground area, the bins must be spaced so they do not shade each other or are shaded by other buildings or trees.

SOLAR DRYING STUDIES IN PROGRESS

Solar drying studies conducted in 1974 and 1975 fall into three categories:

(1) Field testing of the application of solar energy to low-temperature grain drying in storage bins. Solar drying was compared to natural air drying without supplement heat or to low-temperature drying systems using electric heat.

(2) Field testing of low-cost, low-temperature, prototype, solar collectors for heating air for grain drying.

(3) Evaluating the relative potential for solar grain drying in different geographical areas and for different crop conditions by the use of a mathematical simulation model for low-temperature drying.

Field Tests

Eighteen solar-assisted drying tests were conducted with the 1974 crop at eight locations in the North Central region of the United States. One test was with soybeans, two tests were with grain sorghum, and 15 tests were with shelled corn. The tests were typical of low-temperature, in-storage drying, although one test approached conditions similar to batch-in-bin drying. Tests were continued at six locations in 1975.

All of the grain in the solar drying tests was successfully dried to safe storage moisture levels without significant spoilage. In the late fall of 1974, some tests used supplemental electric heat in addition to solar energy. Drying rates with solar systems were adequate to prevent spoilage and were in the range of typical low-temperature drying results—faster than natural air drying and usually a little slower than similar low-temperature systems with a 24-hour continuous temperature rise of 7° to 10°F (4° to 5.5°C).

Final grain-moisture levels were lower in solar tests than in natural-air tests and generally higher than in tests with continuous heat added. In 1974 at the U.S. Grain Marketing Research Center, solar-dried corn averaged 13.2 percent moisture, and corn dried with natural air averaged 14.4 percent moisture after 20 days of drying at 2.5 and 2.8 cfm/bu (2.7 and 3.0 m^3/min-tonne). An inflated tube collector with an area of approximately 300 ft^2 (28 m^2) was used. Typical patterns of drying grain with solar supplemented and natural air are illustrated in figure 14. In Indiana in 1975, with an airflow rate of 2 cfm/bu (2.2 m^3/min-tonne) and 0.8 ft^2 collector per bu (2.8 m^3/tonne), the corn initially at 24 percent averaged 16 percent moisture content after 24 days in the solar bin. With 10° F (5.6° C) added continuously by an electric heater in a companion test, the corn averaged 14.6 percent moisture after 16 days.

Efficiency at which the sensible heat in the drying air was used to remove moisture from grain was calculated for the tests conducted at the U.S. Grain Marketing Research Center. In general, the

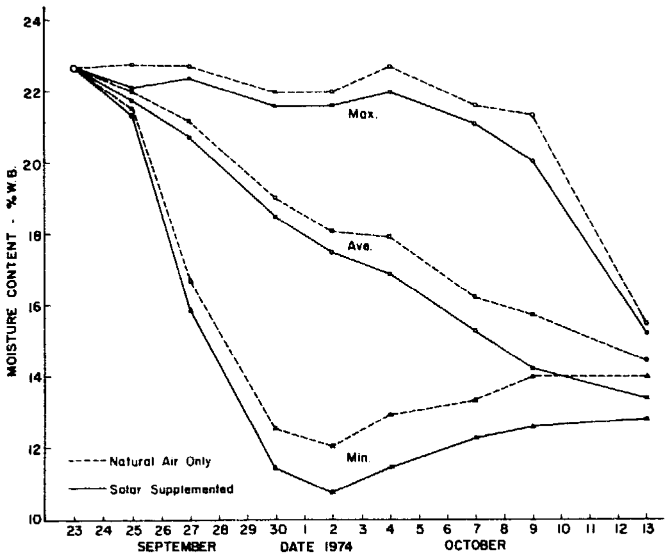


Figure 14.—Typical moisture reduction patterns in corn dried with natural and solar heated air.

utilization efficiency[4] of the sensible heat, natural plus solar, was equal to or a little higher than that in the natural air tests without solar heat. However, the heat utilization efficiency among different tests varied from 14 to 46 percent, a wide range and somewhat lower than anticipated. About 20 percent of the total heat available for drying was from the solar collectors. The other 80 percent was the sensible heat in the air plus the heat from fan energy.

In the Indiana test in 1975, the solar energy collected by two 1,000 ft^2 (93 m^2) units saved approximately 5 cents per bushel in electric energy costs compared to low-temperature, electric drying. The solar collector investment represented about $1.50 per bushel ($57/tonne). This was a relatively high-cost collector, however. In Iowa, a 250 ft^2 (23.2m^2) flat-plate collector supplied 18 percent of the drying energy and reduced the cost of drying 3,440 bu (90.5 tonnes) of corn by 2 cents per bushel ($0.76/tonne) compared to low-temperature drying with electric heat. In South Dakota tests, 26 percent less electrical energy was used in the solar bin than in the check bin in 1974 and 55 percent less in 1975. Corn was dried from moisture levels of about 20 percent to about 14 percent in these tests.

In Ohio, tests were conducted with a system that approached batch-in-bin drying. Depending on the amount of grain placed in the bin, the airflow ranged from 4 to 11 cfm/bu (4.3 to 11.84 m^3/min-tonne). Drying time varied from about 100 to 700 hours. From 1 to 4 ft^2 of collector area was used for each bushel dried (3.5 to 14.1 m^2/tonne).

Through computer simulation, a batch drying system with a capacity of 800 bu (21 tonnes) per day at a moisture content reduction of 5 percentage points (20.5 to 15.5 percent) was investigated in Ohio (*12*). For a solar collector of 10,000 ft^2 (929 m^2) the projected drying cost was 23.8 cents per bushel ($9.04/tonne). With propane gas, the projected cost was 15.1 cents per bushel ($5.74/tonne), with electricity the estimated cost was 24.9 cents per bushel ($9.46/tonne). Propane was priced at $0.35/gal ($0.09/liter), electricity at $0.0365/kWh, and the solar collector at $1.80/ft^2 ($19.38/m^2). In each case, drying from 20.5 to 15.5 percent moisture content was assumed to be by natural air in a storage bin.

Cost effectiveness of solar energy with 1974-75 energy prices and availability was not outstanding. As energy costs go up and collector designs are refined to reduce costs per unit of heat collected, the cost of solar energy relative to other fuels will improve. Naturally, solar collectors are more expensive in their developmental stage, and LP gas and electrical energy costs are relatively low in the Midwest, especially in comparison to grain prices. Typical high temperature corn drying costs in 1975 were 15 cents per bushel ($5.70/tonne) for 10 percentage points moisture removal—half fuel cost and half equipment cost. This was 5 to 6 percent of the grain price.

Investigators at Colorado State University are studying the feasibility of multiple uses of solar energy on the farm. They propose to develop a prototype, multiple use, solar system that will be used for space heating, water heating, and forage drying, as well as for grain drying. Another form of multiple use that has been suggested involves drying inside a greenhouse or similar structure with the structure serving as the solar collector. A combination air-inflated storage, solar collector and grain dryer is being investigated in studies at Kansas State University. These multiple use approaches are being investigated in an effort to improve the use factor of the solar collecting equipment, thereby reducing the cost charged to grain drying.

Collector Design and Performance

The performance of pilot-scale solar collectors of various designs was tested at the ARS field station,

[4] Utilization efficiency is defined as the heat utilized for removing moisture from the grain divided by the sensible heat available in the drying air.

Iowa State University, Ames. Both air-supported and rigid-frame collectors were included. Collectors were flat- and curved-plate designs, both covered and bare. Material used included plastic film, rigid plastic, glass, metal, and wood. Collector configurations were varied, but all were 30 feet (9.1 m) long with an effective area of 90 ft^2 (8.4 m^2). Six collectors were built and tested in 1974, and five were retained for testing in 1975 along with five additional models. Four of the new collectors were the flat-plate type, and one was a concentrating type. A view of the collectors and the test site is in figure 15.

One conclusion from the work at Ames was that collector performance during the fall drying season was approximately doubled by tilting the collector toward the sun at the optimum angle. Performance was also approximately doubled for covered collectors compared with bare plate collectors. Highest efficiencies were obtained with suspended plate collectors with covers and back insulation.

The effect of the cover on tube-type collectors was investigated at the U.S. Grain Marketing Research Center. Data collected showed that adding the clear plastic cover over a single exposed black plastic absorber tube increased by 50 percent the amount of energy collected and retained in a tube approximately 3 feet (0.91 m) in diameter and 100 ft (30.5 m) long.

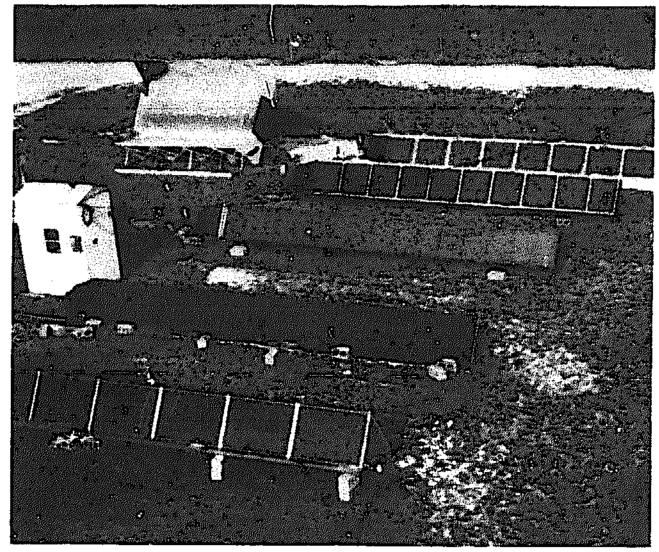
Simulation Test Results

A mathematical model that simulates low-temperature drying of grain (22) was employed to determine the relative effect of crop and weather conditions, including solar energy available, on the airflow and heat requirements for this drying method. The simulation used 10 years of official weather data for one location in each of the North Central States. Probability of success was established for the drying conditions simulated. The criteria of success were based on drying the wettest layer to 15 percent moisture content and on limiting dry matter losses to less than 0.5 percent.

Table 1 gives the simulation results in terms of airflow rate required to dry 24 percent moisture corn harvested on October 15. The airflow data are given in terms of requirements for the next to worst year out of 10 (90 percent success probability) and for the worst year (100 percent success probability).

Airflow rates are given for drying with natural air, with solar heated air (daily average temperature rise of 3 F° (1.7C°) with 1,107 Btu/ft^2-day (300 langleys/day) of incoming solar radiation on a horizontal surface), and with a constant temperature rise of 3° F (1.7° C). In all cases, the heat from the drying fan was assumed to raise the air temperature 2° F (1.1° C). In practice, the temperature rise from the fan is a function of the airflow if grain depth is held constant.

Simulation results indicate that selecting the proper airflow rate for low-temperature grain drying is the single most important requirement to



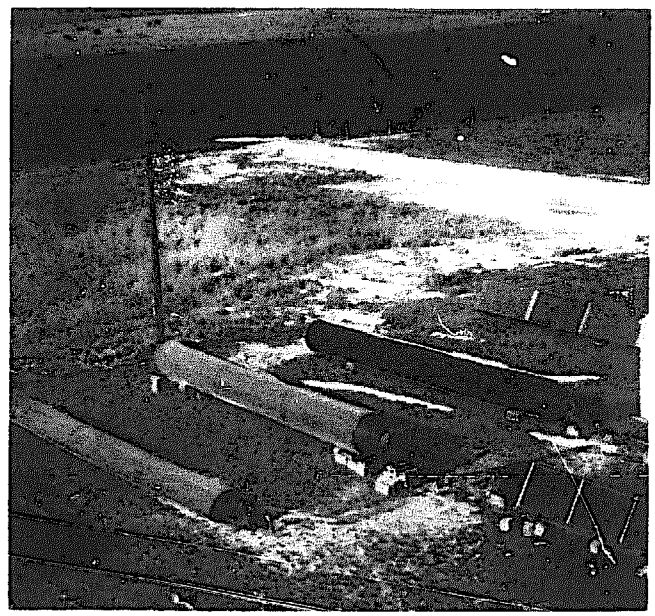


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Figure 15.—The pilot-scale solar collectors tested by ARS at Ames, Iowa.

Table 1.—*Minimum airflow required to dry 24-percent moisture corn harvested October 15 in 12 North Central States using natural air, solar heat, and electrical heat*[1]

Location	Cubic feet of air per minute required per bushel when drying with					
	Natural air[2]		Solar heat[3]		Electrical heat[4]	
	Next to worst year	Worst year	Next to worst year	Worst year	Next to worst year	Worst year
Chicago, Ill.	2.70	3.03	2.16	2.79	2.23	2.79
Indianapolis, Ind.	2.90	3.68	2.13	2.15	1.76	1.85
Des Moines, Iowa	2.18	4.42	2.25	4.18	1.96	3.70
Dodge City, Kans.	2.22	3.32	2.12	3.11	2.12	3.11
Lansing, Mich.	2.75	3.58	2.30	3.01	2.34	2.58
St. Cloud, Minn...	1.91	3.07	1.76	3.60	1.74	3.35
Columbia, Mo. ...	2.48	2.99	2.78	2.87	2.19	2.79
Lincoln, Nebr.	2.07	4.42	2.00	3.75	1.79	3.82
Bismarck, N. Dak.	.57	.75	.54	.94	.54	.89
Mansfield, Ohio ..	2.55	3.92	1.90	3.39	1.85	3.48
Huron, S. Dak. ...	1.40	2.10	1.21	2.36	1.13	2.43
Madison, Wis.	2.24	2.44	1.87	2.20	1.77	2.22

Note: These data may be converted to metric units (m^3/min-tonne) by multiplying by a factor of 1.11.

[1] Based on computer simulated tests using 10 years of actual weather data. Minimum airflow required to maintain dry matter losses of 0.5 percent or less.

[2] A 2° F (1.1° C) temperature rise from the fan assumed.

[3] Heat supplementation includes the 2° F (1.1° C) from the fan plus that from a solar collector capable of providing a 24-hour average temperature rise of 3° F (1.7° C) from 1,107 Btu/ft^2 (300 langleys-day) of solar radiation on a horizontal surface.

[4] 3° F (1.7° C) of electrical heat plus 2° F (1.1° C) from the fan.

assure success. Changes in weather from year to year can make a threefold difference in the minimum airflow required. Supplemental heat, either from solar radiation or from other sources, did little to reduce airflow requirements. However, moving from North Dakota toward Indiana and Ohio where humidity is higher increases the minimum airflow rates required. Solar energy is more effective in reducing airflow requirements in warmer, more humid areas. The simulation results indicate that adding solar heat reduces the drying time required and increases the probability that drying will be completed during the fall.

Data simulated for Ames, Iowa (table 2) show the effect of harvest date and initial moisture content on the airflow required to complete drying. The earlier the harvest date and the higher the initial moisture content, the higher the airflow rate must be to push the drying front through all the grain before spoilage occurs.

Other simulation work in progress in Indiana, Ohio, Minnesota, Michigan, Kansas, and Arizona (Helio Associates in Tucson), is directed toward verification of simulation models with available experimental data and the development of improved models for solar collector performance and for grain drying.

Table 2.—*Effect of harvest date and initial moisture content on the minimum airflow rate (cfm/bu) required to dry corn with less than 0.5 percent dry matter loss,*[1] *Ames, Iowa*

Initial moisture content	Oct. 1		Oct. 15		Nov. 1	
	Next to worst year	Worst year	Next to worst year	Worst year	Next to worst year	Worst year
20	—	—	0.58	0.91	—	—
22	—	—	1.32	1.64	—	—
24	2.61	4.09	2.18	4.42	1.08	3.51
26	—	—	4.89	6.96	—	—

Note: These data are given in cfm/bu. To convert to metric equivalent (m^3/min-tonne) multiply by 1.11.

[1] Based on 10 years of simulated tests with natural air.

FUTURE OF SOLAR GRAIN DRYING

The adoption rate of solar grain drying depends on the supply and price of fossil fuel as well as the availability or allocation of scarce fuel supplies to agricultural production. The relative weight given to other uses of energy in agriculture in relation to crop drying will also be a determining factor. Which is most productive: to allot fuel for powering field operations, for manufacturing fertilizer, or for stationary use as heat?

Obviously, the supply of conventional fuels, especially petroleum, will diminish. Also, such energy intensive operations as grain drying will be under increasing competition for scarce fuels.

The acceptance of solar grain drying will depend greatly on the development of effective and economically viable, solar drying systems. Many avenues of investigation are growing out of current research that must be pursued. Some of these include:

(1) Is some form of energy storage needed for grain drying?

(2) Should solar grain drying systems be devel-

oped that will be suitable for multiple heating uses on farms?

(3) Can solar energy be adapted to high-speed, high-temperature drying systems?

(4) Where and under what conditions can solar energy provide assurance of success with low-temperature drying systems?

When the sun is shining, grain can be dried to safe storage moisture levels of 12 to 14 percent with natural air. Any heat added to the air lowers its relative humidity further and overdries the grain. The overdried grain may be rewet during subsequent ventilation with humid, nighttime air, as discussed earlier. However, the alternate drying and wetting of some grains, notably rice, lowers quality. In rice-drying tests conducted in Texas, a vertical stirring auger moved the dried grain from the active drying layer and mixed it with wetter grain above. Stirring augers also prevented overdrying in corn tests where the amount of solar energy collected provided drying air temperatures more than a few degrees above ambient temperature.

A number of methods exist for storing solar heat. Water, salt solutions, and rock or stone are effective for heat storage. Previous dried grain is a possible storage medium. Solar energy for drying can be stored in the form of regenerated chemical desiccants that may be used later to lower the humidity of air for drying grain.

Obviously, solar systems with provisions for heat storage will cost more. Such systems may need to be used for heating applications other than grain drying to offset their added cost.

What about multiple use? Heat from solar collectors, when not used for grain drying, can be used for heating livestock shelters, farm shops, and dairy buildings, or for forage drying. Hot water for the farm and farm household is a year-round requirement that can be met largely by solar energy. But to adapt a solar grain dryer for water heating requires an air-to-water heat exchanger, an added cost. Other deterrents to multiple use include the need for heat storage in many applications and the bigger problem of getting the heat to where it is needed. Ducting warm air long distances is costly or heat losses are excessive. Portable collectors are a possibility if heat storage is not needed.

High-speed continuous-flow, batch or batch-in-bin drying systems developed for operating only when high levels of solar energy are available may be possible alternatives to low-temperature, in-storage, drying systems. Although large solar collectors would be required, several lots of grain could be dried with the same equipment, and the cost per unit thus reduced. Contrasted with in-storage systems where only limited heat can be applied if overdrying is to be prevented, the grain in batch and continuous-flow systems is dried in relatively shallow layers. Then the overdried and underdried grain is mixed when the dryer is unloaded to achieve the desired final average moisture content.

Field tests under this program started with using solar energy to supplement the heat in natural air for in-storage drying. Because natural air supplies a large part of the heat required for drying by this method, the objective was to use solar energy for the additional heat necessary to provide a reliable, all natural, drying system. However, the need for added heat varies.

In Kansas, for example, grain can be dried with natural air most of the time. Adding a little extra fan power probably provides more assurance of success than adding small amounts of heat. Farther north, a small amount of added solar heat is not always adequate and needs to be backed up by supplemental heat from other sources.

In more humid areas, heat is needed to lower the humidity so drying can proceed. In these areas, solar heat supplementation for in-storage drying systems should find early acceptance. As fuel supplies decrease and prices increase, solar grain drying should be well tested and ready as a viable alternative.

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