The Performance and Economic Feasibility of Solar Grain Drying Systems

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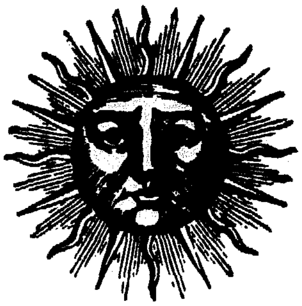

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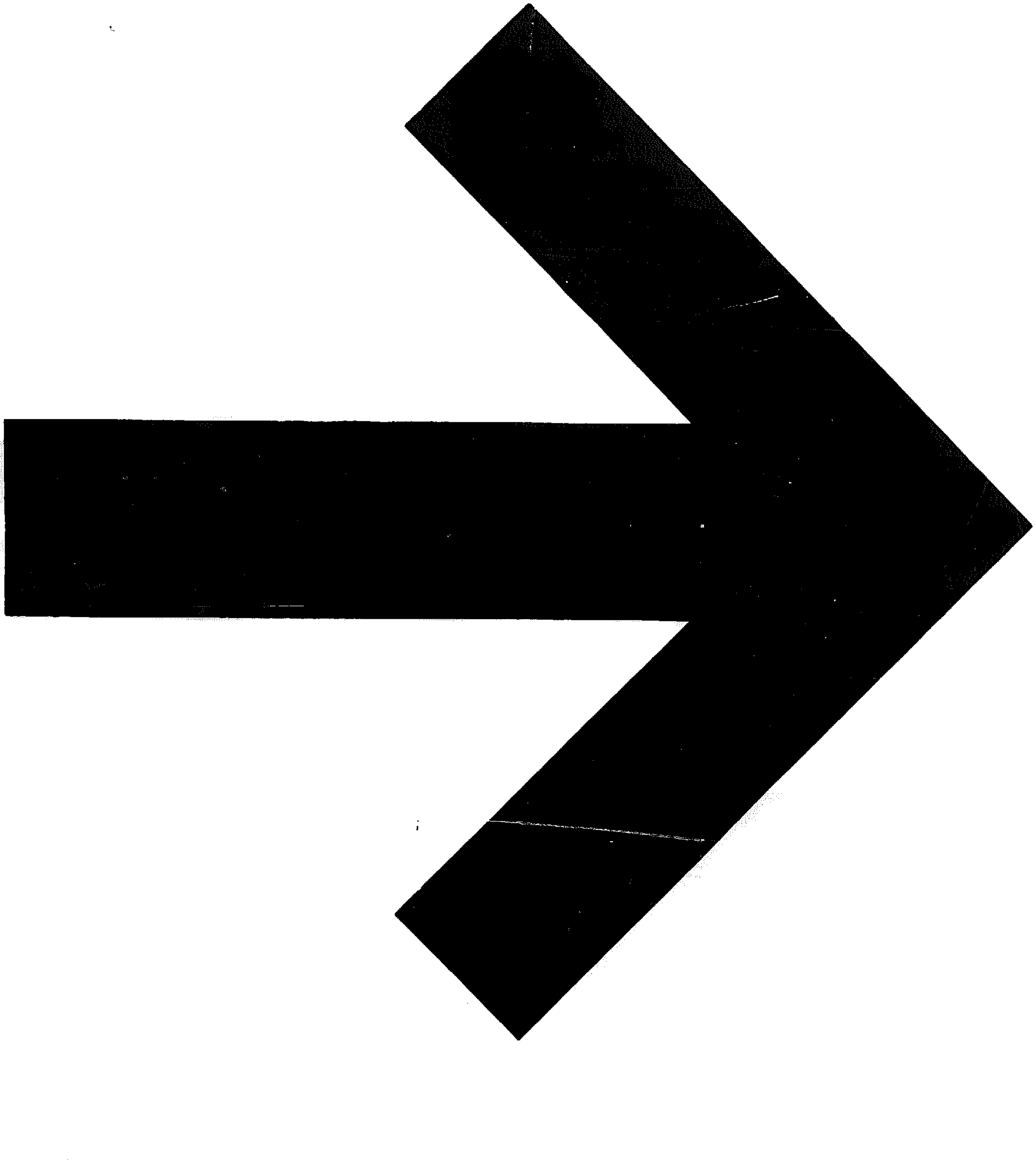
ABSTRACT

The performance and costs of eight experimental onfarm solar collectors designed to dry corn were studied. Solar drying costs were compared with costs of owning and operating conventional grain dryers. The costs of the lowest cost collectors were found to be as low as or lower than those for some conventional dryers. Depreciation and fuel costs were the major cost items contributing to this favorable comparison. Fixed costs for the eight solar collectors ranged from 6.6 to 26.6 cents/bu; variable costs ranged from 1.5 to 8.4 cents. Further research, mass production, and increasing energy costs should enhance the economic feasibility of solar grain drying. However, its dependability on sunshine and the uncertainty of solar performance in times of inclement weather are factors which may limit its use to a "solar grain drying belt."

Key words: Solar, Corn, Drying, Collectors, Costs, Performance, Energy, Economic feasibility.

On January 1, 1978, three USDA agencies--the Economic Research Service, the Statistical Reporting Service, and the Farmer Cooperative Service--merged into a new organization, the Economics, Statistics, and Cooperatives Service.

Washington, D.C. 20250 February 1978



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ACKNOWLEDGMENTS

The author is indebted to the agricultural engineers who conducted the eight solar drying experiments analyzed in this report.

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SUMMARY

Costs of efficient solar collectors came reasonably close to those of some propane gas-powered systems now used. Based on analysis of eight experimental solar drying systems developed by engineers in the Midwest, sun-powered systems represent an investment choice for some grain producers, especially if fossil fuels get scarcer and more expensive. These findings apply for grain farms 40-400 acres in size, roughly 85-90 percent of all grain farms.

Costs are not yet so low that farmers would want to replace usable conventional dryers. But grain producers in some locations might want to consider them to replace wornout systems or add to current capacity. Homemade collectors could be built for $1 to $2 per square foot of collector surface. Commercially constructed collectors could cost $3 to $6 per square foot, based on 1976 costs.

One drawback: homemade solar collectors usually do not last as long as the commercial models, making annual fixed costs higher. These ranged from 6.6 to 26.6 cents/bu based on 1976 costs, while variable costs ranged from 1.5 to 8.4 cents. The greatest potential for cost reduction is in fixed costs, however. Investment costs, for example, will drop further as engineers improve the efficiency of the experimental models, demand increases, and mass production methods can be used.

A primary limit on use of sun-based systems is their susceptibility to weather conditions, not the case for totally fuel-powered methods. Thus, solar methods may be restricted to parts of the country with the most favorable weather conditions. Another problem--that solar collector surfaces are derived from fossil fuels--may be solved through research underway on other types of surfaces, such as glass.

The eight solar drying systems represent a sample of current experiments by engineers across the Nation. Some of the experiments handled as much corn as might be produced on 50 acres, but results could apply to larger farms and other grains. Because these experiments were conducted independently of one another and environmental conditions differed at each site, costs for each should be viewed as a separate case study not comparable with any of the others.

Additional factors could affect the economies of solar drying. Two that merit further study are:

Multiuse--For what other uses can the solar drying system be used--through portability or farmstead layout--about 10 months each year?

Economies of size--Do these exist? Can large volumes of high-moisture corn and other grains be dried using the low-temperature methods necessary in solar-powered systems?

THE PERFORMANCE AND ECONOMIC FEASIBILITY OF SOLAR GRAIN DRYING SYSTEMS

Walter G. Heid, Jr.*

INTRODUCTION

Although information is available on the engineering design of solar collectors and their ability to dry grain, little is known about the cost of present design construction as well as operating costs. The objectives of this study are to fill this void. They are to (1) describe the system design and performance of several different types of drying systems using solar collectors; (2) show costs; (3) compare these costs to those of conventional drying methods using liquefied petroleum gas (LPG) or natural gas; and (4) estimate energy savings and payout time. The economic portions of this study offer the first known cost analyses of solar collectors designed for grain drying.

Crop drying is an important function on many grain farms, especially in the more humid areas of the Corn Belt. With the high cost of harvesting equipment and low margins of profit, farmers are deeply concerned with getting their crops out of the field as soon as possible to avoid in-field losses and obtain a better price for their commodity. This may mean harvesting grain with a moisture content too high for safe storage and, in turn, necessitate drying. If so, a decision concerning location and method of artificial drying must be made. Grain may be dried on the farm or at a local country elevator. Usually, farmers prefer to dry their grain crops on the farm rather than sell high moisture grain to the local elevator and take a discount. It is expensive to transport grain to the local elevator, have it dried, and then returned to a farm for storage. Each time grain is handled there are economic losses because of damaged kernels and spilled grain. It is not desirable to move grain off the farm for drying, especially if the farmer has storage space and does not intend to sell his grain immediately after harvest.

A larger proportion of the annual corn crop is dried than of any other grain. In Illinois, for example, approximately 87 percent of all corn is dried. About 88 percent of all corn in Indiana and 71 percent in Iowa is dried (table 1). For soybeans, only 10 to 15 percent is normally dried on the farm.

In recent years, continuous flow type dryers have increased in popularity while forced air systems using no supplemental heat have declined in importance. Currently, about 50-60 percent of the grain dried on farms is dried in storage bins by batch-in-bin, layer drying, and full-bin low temperature drying methods.

LPG and natural gas are the most common types of fuel currently used. Electricity is used primarily to operate dryer fans. It takes approximately 15 ft^3 (cubic feet) of natural gas or about 0.12 gal of LPG to dry a bushel of corn from 25.0 to 15.0 percent

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*Walter G. Heid, Jr., is an agricultural economist, ESCS, stationed at the U.S. Grain Marketing Research Center, Manhattan, Kansas.

Table 1--Methods of handling corn at harvest, estimates for selected States, 1976

State	Disposition at harvest			Drying practices			
	Marketed direct from field	Farm stored	Total	Not dried	Dried on farm	Dried off farm	Total
	Percent						
Illinois	19.0	81.0	100.0	13.0	85.0	2.0	100.0
Indiana	25.6	74.4	100.0	11.8	86.6	1.6	100.0
Iowa	11.8	88.2	100.0	29.3	68.9	1.8	100.0

Source: Indiana Crop and Livestock Reporting Service, Field Crops, Corn, 1976; Harvesting, Handling and Drying Methods, Statistical Reporting Service, Lafayette, Ind., March 4, 1977.

moisture, an acceptable level of moisture for marketing corn. In 1976, the cost of LPG in Kansas was 27.4 cents/gal while the price of natural gas was \$1.26/1,000 ft^3. 1/ In comparison, these prices were 12.9 cents/gal and \$.77/1,000 ft^3 respectively in 1970. Electricity, relative to LPG or natural gas, is virtually cost prohibitive for drying grains. Using 1976 rates, the electricity cost to produce 1,000 Btu was 4.4 times the cost of LPG and 10.2 times the cost of natural gas. 2/ Natural air, of course, is least expensive, but its use is limited to favorable climatic regions or conditions, and usually it must be supplemented with some form of heat in case of bad drying weather.

Interest in alternative grain drying methods is growing because of the increasing price of conventional fuels and the threat of short supplies in the future. Solar energy is one such alternative. Since it is a relatively new technology as applied to agriculture, procedures for harnessing this energy source are undergoing rapid change.

In response to the interest in new and lower cost methods of drying grain, numerous experiments are being made by agricultural experiment stations, USDA's Science and Education Administration (SEA), private industry, and farmers. With the threat of oil and other fuel shortages in the last 3 to 4 years, solar drying and heating research in general has been stepped up. Many of the technological or engineering improvements in collector design may be adapted to a broad array of uses, including agriculture. In agriculture, solar energy is being considered for greenhouse operation, food processing, forage drying, irrigation purposes, and heating livestock shelters, farm shops, farm homes, and water. Some researchers have treated these end uses singularly, while others have worked on a multiple-use concept. Federal funds for much of this and other solar-related research are being made available through the Energy Research and Development Administration (ERDA). This study was made in close cooperation with SEA and agricultural experiment station engineers and was partially funded by ERDA.

1/ Kansas rates for 1,000-gal deliveries of LPG and for the use of between 1,001 and 29,000 ft^3 of natural gas.

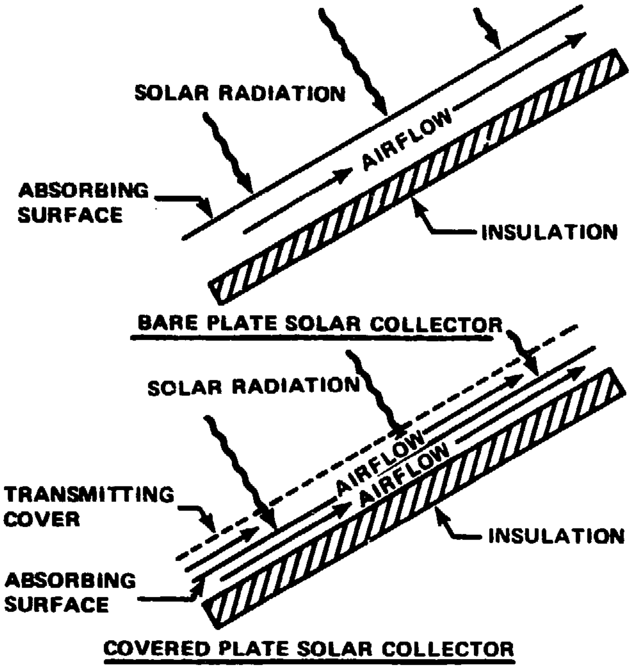
2/ These relative measures will differ from State to State because of differences in utility rates and fuel prices.

ANALYTICAL PROCEDURES

Data which serve as a basis for estimating the capital investment and unit costs presented in this study were obtained from experimental designs developed by agricultural engineers (see Acknowledgments). Cost estimates are developed for eight solar collectors now being tested by the Science and Education Administration in Kansas and agricultural experiment stations in South Dakota, Iowa, Ohio, and Colorado. The collectors 3/ are: (1) rock heat-storage, (2) flat-plate, (3) inflated tube, (4) suspended plate, (5) wraparound, 4/ (6) intensifier, (7) air-supported, 4/ and (8) multiuse. 4/ For each system, the design, measure of performance, capital investment, and fixed and variable costs are presented. Descriptions of the design and performance of each collector are included to provide technical information to the reader.

The basic parts of a solar collector are shown schematically in figure 1. Solar energy collectors utilize air as the medium for transporting heat. The difference between the bare plate collector and the covered plate collector is the additional transmitting cover on the latter. A covered plate is more expensive to construct but also more efficient. Energy emitted from the face of a bare plate is lost since it reradiates to the atmosphere.

The transmitting cover is usually glass or clear plastic. The absorbing surface may be metal, wood paper, plastic, or even rock. It is a common practice to insulate the back or bottom of solar collectors, but it is not feasible to insulate certain collectors because of their design. Not all experimental solar collectors are constructed using the flat plate design. Another common design is the tubular collector. This type of collector is either air inflated or supported on a light frame. Tubular collectors normally employ a black plastic absorber tube inside a clear plastic tube. The design of each of the eight solar collectors included in this study is described and illustrated in the next section.



Source: G. H. Foster and R. M. Peart, Solar Grain Drying: Progress and Potential, AIB-401, Agricultural Research Service, U.S. Department of Agriculture, November 1976

Figure 1
Schematic of bare plate and covered plate solar collectors for heating air

A grain drying-storage system is composed of all the bins and equipment used in the drying and storage function. It may include a dump pit; augers for load in, interbin transfer, and load out; a solar collector; fan(s); transition(s) (connecting air duct(s)); duct work; perforated drying floor; drying bin; stirrers; spreaders; and storage bin(s). However, this study is concerned only with the additions to the system that are necessary for grain drying. Only the costs of the solar collector, the related duct work, transition(s), electric fan(s), costs for land (space), fencing, fan houses, tie

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3/ These names are used to distinguish between the eight collectors and may not be a totally accurate description in some cases.

4/ These solar collectors were designed and built by commercial firms.

downs, and electrical hookups are included in this analysis. 5/

The brief descriptions of the design and performance of each system, along with the illustrations, should be especially helpful to the researcher interested in constructing a solar collector and installing a solar grain drying system. For further information about these and other solar grain drying systems, see Foster and Peart, Solar Grain Drying: Progress and Potential, AIB-401, Agr. Res. Serv., U.S. Dept. Agr., Nov. 1976.

Investment costs of each system included in this study were determined either by developing a list of materials necessary for the particular system and then pricing the items or for commercial collectors or their parts, by obtaining estimates of production costs. Repair and maintenance and life expectancy estimates were obtained from the engineers conducting the experiments and from personal observations. The cost analysis itself involves simple budgeting techniques. Buildings and equipment were depreciated at a straight-line rate. Cost of insurance was calculated using a combined premium for fire and extended coverage of $6 per $1,000 valuation. Rates and valuation were obtained from insurance agents and county assessors, respectively. Taxes were calculated using an assessed valuation of 30 percent of original cost and a rate of 65 mills. Although some system designs would place the collector in a personal property tax classification, the property tax calculation was used for all systems. Interest on investment was charged at 8 percent of one-half the original cost of the collector, equipment, electrical hookup, and fencing and at 8 percent for total land cost.

Direct labor was omitted from the variable costs because the only labor required in the drying operation was to measure moisture of the corn. Further, if an assumption of a given amount of labor per day had been made, the small volume experiments would have been unjustly penalized. Labor was included in the comparison of solar and conventional systems as shown in the appendix. All labor used to set up or dismantle the collector was included in the maintenance and repairs category. Interest on working capital was calculated at a rate of 8 percent for a loan period of 3 months. The current electricity rates of the State in which the experiment was conducted were used. These varied from 1.75 cents/kWh to 4.5 cents/kWh.

After discussing each of the eight solar drying systems separately, costs of the flat-plate solar system (a medium-cost system) and the wraparound solar system (a low-cost system) are compared with those of two conventional drying systems. Costs of conventional dryers were computed from information obtained from manufacturers. These cost estimates were compared with recent cost estimates made in both Illinois and Kansas.

Finally, recent trends in natural gas, LPG, and electricity are shown. These trends are then interpreted in terms of payout time for the wraparound system using an assumption of a fuel cost increase in the near future of 5 percent compounded annually.

The problem of grain quality change was not addressed in this study. Generally, if corn is to be marketed, it is desirable to reduce the moisture content to approximately 15 percent. However, if corn is to be stored on the farm, then the moisture content should be lowered to 13 percent.

5/ A supplemental electric heater was used and therefore included in the cost analysis of the suspended plate collector. For the multiuse solar collector, the costs of a rock heat-storage bin and a two-wheel trailer were included.

PERFORMANCE AND COST ANALYSIS OF EIGHT SOLAR GRAIN DRYING SYSTEMS

This section describes in detail the collector design, drying performance, and costs of each of eight solar grain drying systems. Tables 2-5 give comprehensive data describing the drying parameters, capital investment costs, and estimated costs of owning and operating each of the eight solar collectors. The reader can refer to these tables as each collector is discussed. Procedures for computing costs of two solar collectors and two conventional dryers are shown in the appendix.

Although costs for the various solar collectors are presented side by side, they should not be compared to one another for the following reasons:

- First-generation experimental units do not represent optimum equipment packages. (Bin sizes may not properly match collector capacity, for example, because in the early phases of research engineers may utilize pieces of equipment already available.
- The volume of corn dried was not the same in all experiments.
- The moisture content of the corn differed, as did the amount of moisture extracted.
- Solar heat was not utilized at the same percentage of capacity by all systems.
- The systems have varied and uncertain life expectancies at this stage in their development.
- Fan size and air velocity varied by experiment.
- Weather conditions were not uniform at all locations.
- Costs of materials and electricity varied from location to location.
- Operating costs at a given location will vary from year to year depending on weather conditions.

More important, the costs of each solar system should be viewed with regard to short-run vs. long-run considerations, the relative magnitude of cost items, their cost level relative to conventional drying costs, and the cost or amount of nonrenewable energy saved. By comparing fixed and variable costs certain strengths and weaknesses in the economic efficiency of each collector system may be determined. For example, a solar collector that is economically efficient in terms of short-run operating costs or energy consumption, per se, may not be the least expensive type in the long run.

A large-cost item may have the potential for greater reduction than a small-cost item. Also, awareness of large-cost items for each collector may enable engineers to focus their attention on high-cost items. At this early stage in the development of solar collectors and systems design, there is much latitude for experimenting with new materials and design. This experimentation was found to be more advanced at some locations than at others.

Most early prototype solar collectors being developed by agricultual engineers have been planned with major emphasis on keeping investment and operating costs low to the farmer as opposed to an emphasis on efficient utilization of solar energy. Furthermore, the cost to early innovators and development engineers may be different from costs of second- or third-generation structures or mass-produced structures. Costs will change over time as system designers choose more durable materials, and initial investments will likely increase while annual fixed costs will decrease. Thus, the costs in this analysis should not be viewed as exact. Instead, they are guidelines to future engineering designers or farmers involved in building solar collectors.

Rock Heat-Storage

System Design

The rock heat-storage collector was a combination collector-heat storage unit containing 32 tons of fist-size, screened limestone rocks serving as a heat storage medium. Dimensions of the collector were 12 ft by 28 ft (336 ft^2 of collector surface). The collector surface was made of 7-ounce clear fiberglass panels which formed

Table 2--Drying performance, eight selected solar grain drying systems, 1976

System	Bin size		Floor area	Batches	Volume (wet basis)	Beginning moisture	Total drying time	Ending moisture	Moisture reduction	Water loss	Volume (dry basis) [1]	Total electricity
	Bushels	Diameter in feet	Ft^2	No.	Bushels	Pct.	Days	---Pct.	---Pct.---	Pounds	Bushels	kWh
Rock heat-storage	1,000	15	177	2	1,502	22.4	30	14.5	7.9	7,772	1,363	462
Flat-plate	2,600	18	254	2	5,029	21.0	22	11.5	9.5	30,235	4,489	3,538
Inflated tube	1,000	15	177	2	1,548	23.8	30	12.3	11.5	11,367	1,345	468
Suspended plate	3,500	18	254	1	3,440	19.8	44	14.4	5.4	12,153	3,223	8,783
Wraparound	5,000	23	434	4	5,200	20.5	18	14.5	6.0	20,435	4,835	4,680
Intensifier	1,400	18	254	1	1,300	32.8	22	16.4	16.4	14,281	1,045	1,936
Air-supported	8,000	24	452	4	6,720	20.9	24	15.2	5.7	25,295	6,268	5,040
Multiuse	150	6	28	2	260	25.5	37	15.0	10.5	1,799	228	520

System	Electricity/100 lb H_2O removed	Electricity/bu (wet basis)	Electricity/bu point moisture removed	Collector surface	Ratio of collector surface to bin		Fan size	Air flow through collector		Air flow through grain	Bin floor area air velocity
	----------kWh	----------kWh----------	----------kWh	Ft^2	Floor area	Volume	Hp	Cfm	Cfm/ft^2	Cfm/bu	Fpm/ft^2
Rock heat-storage	5.9	0.67	0.07	336	1:0.53	1: 2.98	0.75	1,910	5.68	2.54	10.79
Flat-plate	11.7	0.70	0.07	320	1:0.79	1: 8.12	[2]8.00	2,750	8.59	2.60	[3]
Inflated tube	4.1	0.67	0.07	170	1:1.04	1: 5.88	0.75	1,770	10.41	2.29	10.00
Suspended plate	72.0	2.60	0.47	256	1:0.99	1:13.67	5.00	4,400	17.19	1.28	17.32
Wraparound	22.9	0.90	0.15	681	1:0.64	1: 7.34	10.00	12,000	17.62	9.23	27.65
Intensifier	13.5	1.49	0.09	384	1:0.66	1: 3.65	3.00	2,000	5.21	1.54	7.87
Air-supported	45.3	1.71	0.30	960	1:0.47	1: 8.33	3.00	3,960	1.88	1.07	11.68
Multiuse	28.9	2.28	0.22	78	1:0.36	1: 1.92	0.17	300	3.85	2.31	10.71

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[1] Original volume x $\frac{\text{100 minus the wet percentage moisture}}{\text{100 minus the dry percentage moisture}}$ = volume of dry corn.

[2] An additional 8-hp fan was located between the two drying bins used in this experiment.

[3] For the first batch, air velocity was 24.4 fpm/ft^2 of bin space. For second batch in daytime (8 hours) air velocity was 26.7 fpm/ft^2 of bin space. At nighttime (16 hours) when only natural air was being forced into the grain, 18.9 fpm/ft^2 of bin space was used.

Table 3--Capital investment in eight selected solar grain drying systems, 1976

Cost item	Rock heat-storage	Flat-plate	Inflated tube	Suspended plate	Wraparound	Intensifier	Air-supported	Multi-use
	Dollars							
Collector 1/	2,055	1,482	187	228	1,900	1,405	2,000	2/1,276
Equipment 3/	196	1,170	196	4/900	1,193	593	480	575
Electrical hookup 5/	400	400	400	400	400	400	400	400
Fencing 6/	89	89	94	91	--	91	94	66
Land (space) 7/	33	33	32	45	11	45	32	20
Total	2,773	3,174	909	1,664	3,504	2,461	3,006	2,337

1/ Including installation labor and freight.
2/ Includes flat-plate collector, a rock storage bin, and a two-wheel trailer.
3/ Includes fan and transition(s).
4/ Includes an electric heater.
5/ Cost of electric panel, meter, and service labor to install. (Assumes electric service company will provide 200-A service to bin and dryer site.)
6/ Estimates are for four-strand barbed wire fence using 7-ft steel line posts, wooden corner posts, and a wire gap entrance.
7/ The cost of space includes the area of enclosure plus a 10-ft drive area along one side for unloading.

Table 4--Collector surface area, life expectancy, and related capital investment estimates for eight selected solar collectors, 1976

System	Total collector surface	Collector capital investment/ft^2 of collector surface 1/	Life expectancy 2/	Collector capital investment/ft^2 of collector surface/ life expectancy
	Ft^2	Dollars	Years	Dollars
Rock heat-storage	336	6.12	20	0.30
Flat-plate	320	4.63	5	.93
Inflated tube	170	0.53	3	.18
Suspended plate	256	.89	5	.18
Wraparound	681	2.79	20	.14
Intensifier	384	3.66	10	.37
Air-supported	960	2.08	6	.35
Multiuse	78	3/12.82	20	.64

1/ Includes the cost of the collector only (see table 3).
2/ Estimates of life expectancy were based on types of materials used in the respective system.
3/ Does not include rock storage bin or two-wheel trailer on which this portable collector was mounted.

Table 5--Estimated costs of owning and operating eight selected solar grain drying systems, 1976

Costs	Type of collector							
	Rock heat-storage	Flat-plate	Inflated tube	Suspended plate	Wraparound	Intensifier	Air-supported	Multiuse
	Cents per bushel							
Fixed:								
Collector depreciation	6.2	5.3	3.6	1.2	1.6	9.7	4.5	3.7
Equipment depreciation	0.9	1.6	0.9	1.7	1.5	3.0	0.5	2.5
Electricity (hookup) 1/	1.3	0.4	1.3	0.6	0.4	1.5	.3	1.3
Insurance on collector and equipment 2/	.9	.3	.2	.2	.4	.9	.3	.7
Interest on investment 3/	7.0	2.6	2.1	2.0	2.6	7.9	2.4	6.0
Taxes (personal property or real estate) 4/	3.4	1.2	1.0	.9	1.3	3.6	1.1	2.8
Total fixed	19.7	11.4	9.1	6.6	7.8	26.6	9.1	17.0
Variable: 5/								
Electricity 6/	1.4	3.2	1.4	6.4	2.2	3.7	1.9	1.3
Repairs and maintenance	2.0	3.2	1.9	1.8	.3	3.1	1.7	.2
Interest on working capital 7/	.1	.1	.1	.2	8/	.1	.1	8/
Total variable	3.5	6.5	3.4	8.4	2.5	6.9	3.7	1.5
Total costs	23.2	17.9	12.5	15.0	10.3	33.5	12.8	18.5
	Bushels							
Bushels dried	1,502	5,029	1,548	3,440	5,200	1,300	6,720	260
	Percent							
Moisture removed	11.2	9/11.4	11.5	5.4	5.5	16.4	5.7	10.5
	Cents per bushel							
Total variable cost/bu/percent moisture removed	.3	.6	.3	1.6	.4	.4	.6	.1

1/ Depreciated at rate of 5 percent per year (20-year life) with 10 percent salvage value. 2/ At rate of $6/$1,000 capital investment. 3/ Calculated at 8 percent of half the original cost of collector, equipment, electricity hookup, fencing, and 8 percent total land cost. 4/ Based on 30 percent of original value (new) and mill rate of 65 ($65 per $1,000 valuation).

5/ Charges for insurance and tax on grain were omitted under the assumption that these costs are associated with the storage function rather than the drying function. Direct labor is omitted from solar drying cost estimates because the only labor required is to measure moisture in grain and if an assumption of a given amount of labor/day is made, the small volume experiments are unjustly penalized. 6/ Rates varied by State. 7/ Based on a rate of 8 percent and a loan period of 3 months. 8/ Less than one cent. 9/ Weighted average of two bins.

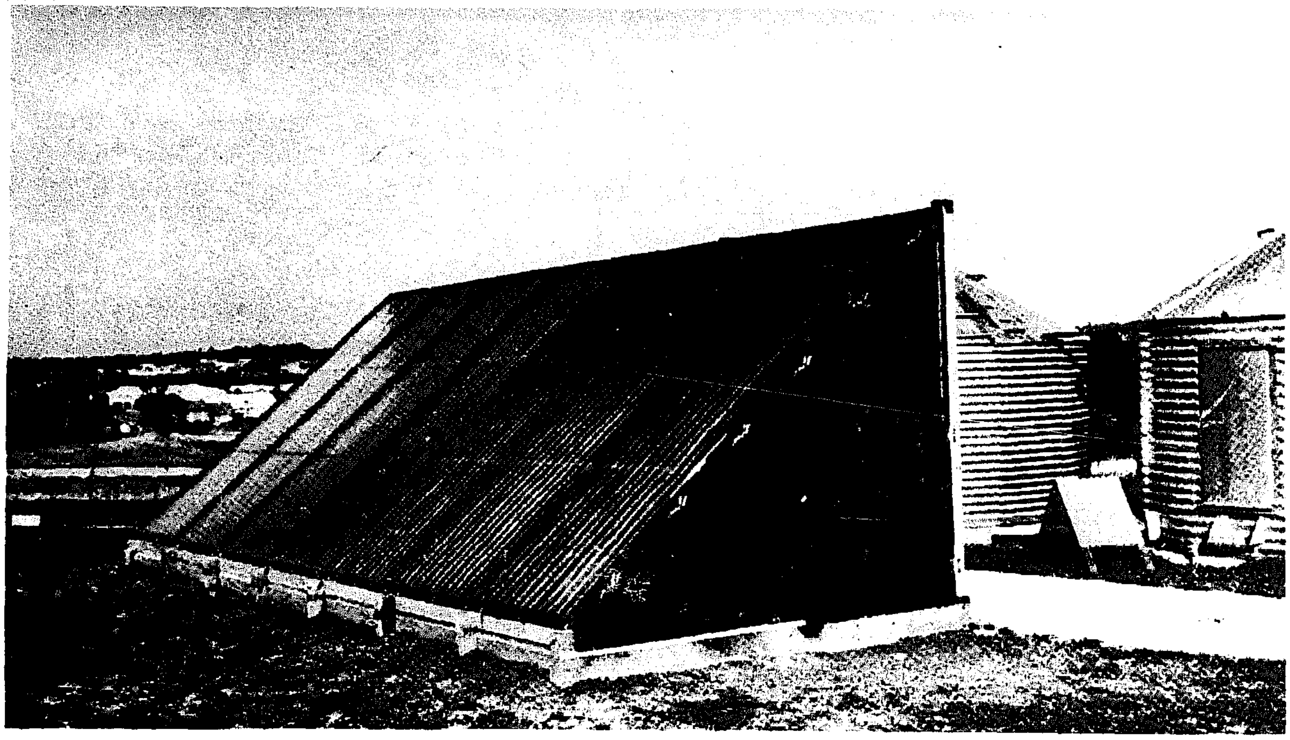

Figure 2
Stationary Rock Heat-Storage Solar System used in corn drying experiment. Location: U.S. Grain Marketing Research Center, Manhattan, Kansas

the covering over the rocks. The surface of the rocks and the interior of the retainer wall were painted flat black and served as the absorber of solar energy. The structure, facing south, was sloped at 40°. The ends as well as the roof of this collector were made of fiberglass (fig. 2). The fiberglass panels, framed with a lightweight angle iron were purchased from a commercial firm which custom produces such items. The structural support of the collector was made of dimension wood lined with 3/4-inch plywood on the north wall next to the rocks. Two 10-ft lengths of 12-inch diameter corrugated perforated ducts were joined by a three-way T duct to move the air into a 12-inch 3/4-hp electric fan located next to the collector. In turn, a connecting insulated duct from the fan to the grain bin supplied the air to the grain. The system air flow design produced 1,910 cubic feet per minute (cfm), or an average of 5.68 cfm/ft^2 of surface area.

Drying Performance

The storage facility used in this experiment was a 7-ft high, 15-ft diameter round steel bin with a capacity of approximately 1,000 bu. The bin was filled to a depth of 5.4 ft with 751 bu of corn, wet basis (w.b.), at one time. The ratio of collector surface to bin volume was 1:2.98 and the ratio of collector surface to bin floor area was 1:0.53. The air flow rate used in the drying process (through the corn) measured 2.54 cfm/bu. The corn averaged 22.4 percent moisture (w.b.) at the beginning of the test. Drying was started on September 28 and continued for 15 days. Final moisture content was 11.2 percent. (For this cost analysis, it is assumed that two batches of corn could be dried by this system within the constraints of the harvest period.) 6/ In total, 0.67 kWh of electricity per bushel was used during the drying period, or 0.07 kWh/bu per percentage point of moisture removed. No supplemental heat was used.

6/ For purposes of determining the volume of corn that could be dried in these experimental systems, it is assumed that the final batch must be placed in the drying system by the end of a 21-day harvest period.

Costs

Capital investment costs for the collector were $2,055. The fiberglass panels including freight charges accounted for nearly half this total. Next in magnitude were the costs of the perforated duct work under the rocks ($309) and the charge for 100 hours of construction labor ($250). Other costs were for lumber, nuts and bolts, rocks, and miscellaneous items. Costs of the fan, transition ducts, fan house, electric hookup, fencing, and land (space) totaled about $718. Total investment costs for the collector itself accounted for 74 percent of the total. The capital investment cost totaled $6.12/ft^2 of collector surface, and the capital investment cost per square foot of collector surface per year of life was $0.30. Total drying cost per bushel was estimated at 23.2 cents.

Fixed cost. The rock heat-storage unit had as long an estimated life, 20 years, as any of the eight collectors studied. It also had one of the highest capital investment costs per square foot of collector surface. With a 20-year assumed life and 10-percent salvage value, depreciation costs per bushel for this collector totaled 6.2 cents, or nearly one-third the total fixed cost. The high investment cost also raised the fixed unit charge for interest on investment. Total fixed cost for the rock heat-storage system was estimated at 19.7 cents/bu.

Variable cost. Total variable cost for the rock heat-storage system was 3.5 cents/bu. Because of the homemade construction of this collector and the probable need for annual maintenance, the repair item, 2 cents/bu, was also a major cost item. The cost of electricity (at the rate of 4.5 cents/kWh) was 1.4 cents/bu, or 0.12 cent/bu per percentage point of moisture removed.

Flat-Plate

System Design

The flat-plate collector was designed in two sections and connected in the middle by a common duct. Both sections are 8 ft by 20 ft, at 160 ft^2 of collector surface each. The two sections are built on runners, making them portable (fig. 3). Materials used included an inner or bottom surface of 1-inch styrofoam sheets resting on a plywood base. The base was separated by a 3-inch airspace from an absorber made of sheet metal panels painted flat black. The sheet metal in one section was a 28-gauge corrugated roofing material. For the other section, an accordian or deep V-shape design was selected. This material was a 20-gauge cold-rolled black iron. An outer cover surface, made of 4-mil transparent glossy polyvinyl, was constructed in the form of 4-ft by 8-ft windows secured in a wooden frame. 7/ The collector surface sloped 40° and was positioned facing south. The two sections were connected by a sheet metal duct which forms a transition duct leading to the fan. An 8-hp axial fan, 24 inches in diameter, was used in this design. A transition duct extending from the fan connected to the plenum of the bin.

This design had one unique feature. After one binful of corn (A) was dried, it was used to store heat with which to dry corn in a second bin (B) located nearby. 8/ An additional 8-hp axial fan and duct system connected the two bins. A gate was used to allow either solar heat or natural air to be forced into bin B. On bin A, only solar heated air was used. On bin B, the drying fan supplied outside air during the day (8 hours), while the collector fan was charging the binful of dried corn with heat from the solar collector. During the night (16 hours), the fan was turned off, the fan intake duct covered,

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7/ Later generation flat-plate collectors have now been designed, using corrugated fiberglass for the outer surface. These have a projected life of 20 years.

8/ In the experiment, while corn in bin A was solar dried, a binful of corn was dried in bin B. The corn in bin B was then loaded out of the bin and the second binful was solar dried. The first bin of corn in bin B was not included in this analysis.

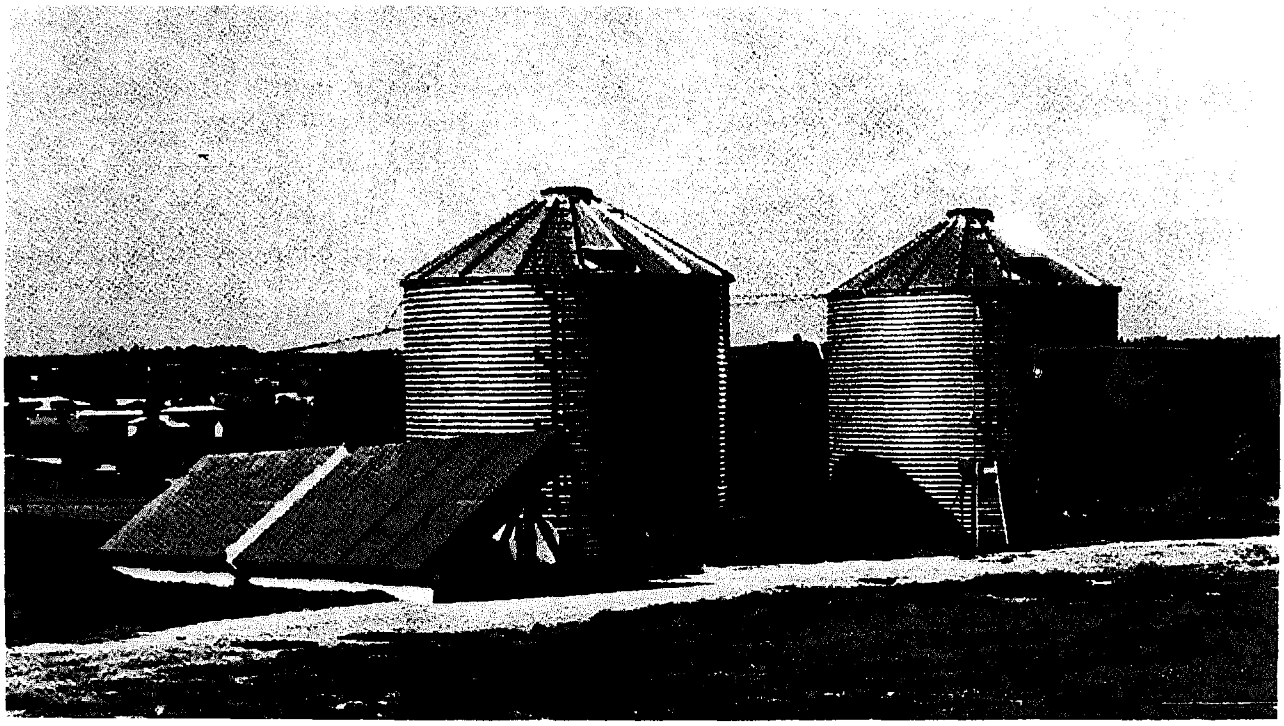

Figure 3
Portable Flat-Plate Solar System used in corn drying experiment, located at U.S. Grain Marketing Research Center, Manhattan, Kansas

the air gate opened between the two bins, the outside air closed off, and heat drawn from the dry corn and forced into the wet corn. (The cost of the intermediate pass-through storage bin is not included as a part of this drying system.) The system's air flow design produced 2,750 cfm for an average of 8.59 cfm/ft^2 of surface area.

Drying Performance

The storage facilities used in this experiment were round steel bins 14 ft high and 18 ft in diameter, with a capacity of approximately 2,500 bu each. Each bin was filled to a depth of approximately 12 ft with about 2,500 bu of shelled corn (w.b.) in a 2-day period. The ratio of collector surface to bin area was 1:8.12 and the ratio of collector surface to bin floor area in this experiment was 1:0.79. The air flow used in the drying process (through the corn) measured from 2.5 to 2.7 cfm/bu. The corn averaged 22 percent moisture (w.b.) in the first bin. Drying was started on September 22 in the first bin and continued for 12 days. When drying was discontinued, the corn contained 11.7 percent moisture. Drying on the second bin was started on October 6 and continued for 10 days. When drying commenced, the corn contained 20.2 percent moisture; when drying was discontinued, the corn contained 11.2 percent moisture. In total, 0.70 kWh of electricity per bushel was used during the drying period, or 0.07 kWh/bu per percentage point of moisture removed. No supplemental heat was used.

Costs

Capital investment cost for the flat-plate collector was $1,482. The major cost item for this complex structure was labor, which accounted for 46 percent of the total cost. Costs of the fans, transition ducts, electrical hookups, fencing, and land (space) totaled an additional $1,692, for a total capital investment cost of $3,174. The two-section flat-plate collector accounted for 63 percent of the total cost. The capital investment cost of this collector came to $4.63/ft^2 of collector surface. The capital investment cost per square foot of collector surface per year of life totaled $0.93. Total system cost per bushel was estimated at 17.9 cents.

Fixed cost. Because the construction was of light-dimension lumber, styrofoam pieces, and polyvinyl panels, the estimated life of this unit was only 5 years with a 10-percent salvage value. Thus, dryer depreciation (5.3 cents) and interest on investment (2.6 cents) accounted for most of the total fixed cost of 11.4 cents. However, since this unit is portable, it might be used for other heating purposes when not needed for corn drying, thus lowering fixed costs charged to grain drying.

Variable cost. Total variable cost per bushel was 6.5 cents. The largest cost items were electricity and repairs and maintenance, totaling 3.2 cents/bu. The cost of electricity (at the rate of 4.5 cents/kWh) was 0.34 cents/bu per percentage point of moisture removed.

Inflated Tube

System Design

This solar collector was a low-profile inflated tube 20 inches in diameter. The outer cover was made of 4-mil clear polyvinyl. The inner liner was constructed of 6-mil black plastic. The 100-ft-long tube had 170 ft^2 of collector surface. A 3/4 hp, 12-inch electric fan located at the intake end served to inflate this collector. Small holes in the inner tube near the bin allowed return air to inflate the outer tube and hold it away from the inner tube. Once the tubes were inflated, the air between them stopped moving and acted as a support.

No transition duct was needed for this low-profile collector, in contrast to similar experiments with high-profile collectors. The inner end was attached directly to the drying bin. To hold down the collector, concrete blocks and 5/16-inch-diameter nylon rope were used (fig. 4). The initial labor for constructing the two-layer

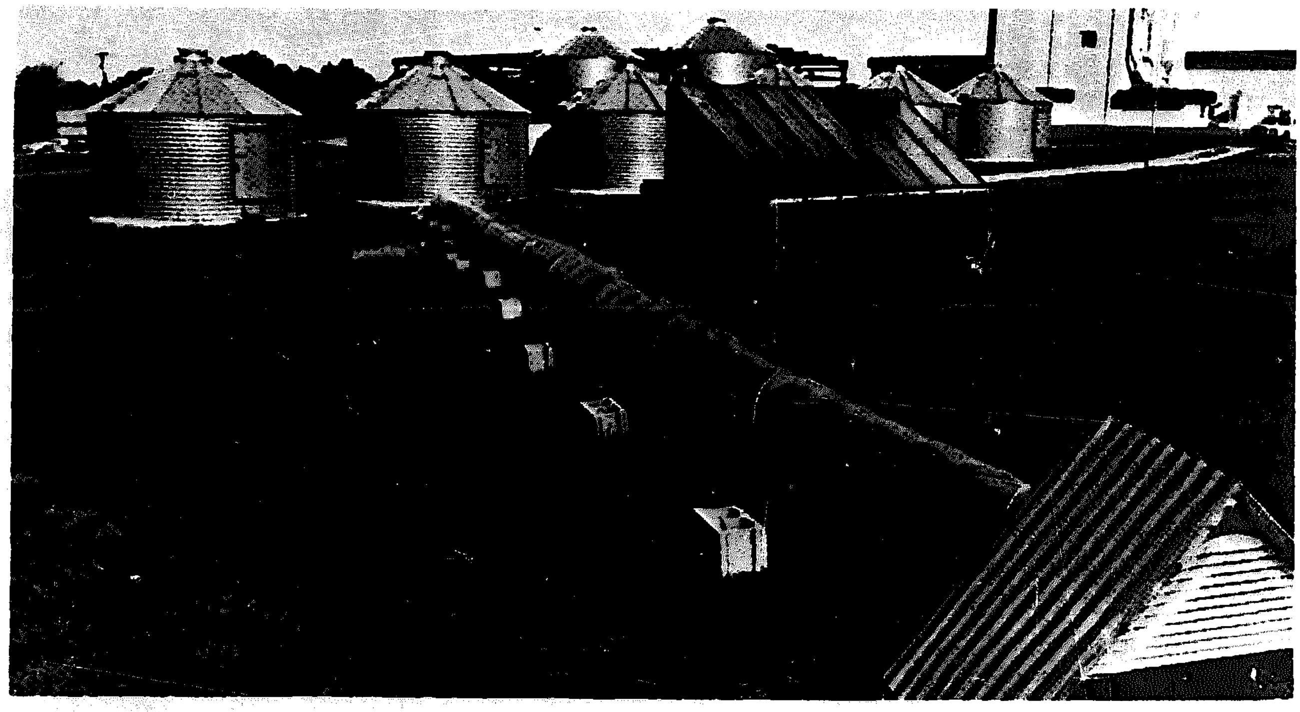

Figure 4
Stationary Inflated Tube Solar System used in corn drying experiment in foreground with another view of the Rock Heat–Storage Solar System in back. Location: U.S. Grain Marketing Research Center, Manhattan, Kansas

tube and placing it into use totaled 16 hours. This relatively simple but nondurable system should be erected and taken down each year, a task requiring approximately 16 hours of labor annually. The system's air flow design produced 1,770 cfm, or an average of 10.41 cfm/ft^2 of surface area.

Drying Performance

The storage facility used in this experiment was a 7-ft high, 15-ft diameter round steel bin with a capacity of 1,000 bu. The bin was filled to a depth of approximately 5 ft with 774 bu of shelled corn (w.b.) in one day. The ratio of collector surface to bin volume was 1:5.88 and the ratio of collector surface to bin floor area in this experiment was 1:1.04. The air flow used in the drying process (through the corn) measured 2.29 cfm/bu. The corn averaged 23.8 percent moisture and was dried to 11.5 percent moisture in 15 days. (For this cost analysis, it was assumed that two batches of corn could be dried by this system within the constraints of the harvest period.)

In total, 0.67 kWh of electricity per bushel was used during the drying period, or 0.07 kWh/bu per percentage point of moisture removed. No supplemental heat was used.

Costs

The inflated-tube system cost the least of those studied. Total capital investment was $909, of which the collector alone cost $187, or 21 percent. The capital investment cost per square foot of collector surface amounted to $0.53, and per year of life, it came to $0.18. Total system cost per bushel was estimated at 12.5 cents.

Fixed cost. The life expectancy of this collector was 3 years with a 10-percent salvage value, even when taken down after use. Because of its short life, system depreciation costs totaled 3.6 cents/bu, or 29 percent of total costs. Selection of more durable materials could increase the life expectancy. Also, at this stage of the experiment, it is too early to estimate how satisfactory repair patches may be. Total fixed costs per bushel were 9.1 cents.

Variable cost. Because of the construction materials used, repairs were the major variable cost item, 1.9 cents/bu, accounting for over one-half of the total variable cost of 3.4 cents/bu. Electrical costs (at the rate of 4.5 cents/kWh) totaled 1.4 cents/bu, or 0.12 cent/bu per percentage point of moisture removed.

Suspended Plate

System Design

This collector was freestanding and optimally tilted, mounted at a 55° slope, with 256 ft^2 of absorber surface. It was constructed from 3/8-inch exterior plywood, dimension lumber, and 6-mil polyethylene plastic film. The unit was built in two sections, each 4 ft wide and 32 ft long. Black polyethylene was stretched over each trough-like section to provide a suspended plate absorbing surface and to form a lower air duct (fig. 5). A clear polyethylene cover supported on arched wooden ribs enclosed the upper air passage. No insulation was added to the back of the collector. Support frames were constructed and alined on an east-west axis to provide south facing collector mounts.

The two collector sections were ducted to the dryer fan intake by means of a plywood junction box, to allow drying air to be drawn in at the ends of the collector and through the air space on either side of the suspended absorber surface to the centrally located fan intake.

Outdoor exposure from November to April caused no significant deterioration of the collector other than of the clear plastic covering. A comparison of radiation attenuation through the

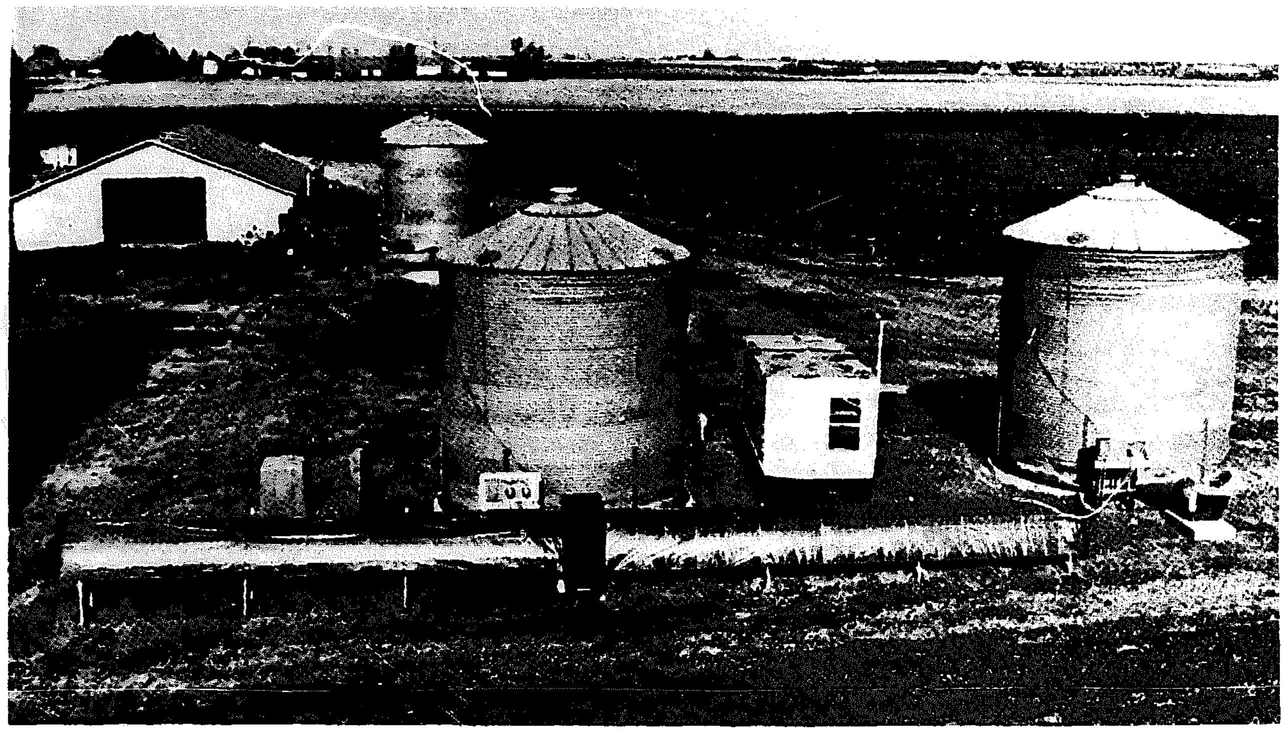

Figure 5
Stationary Suspended Plate Solar System used in corn drying experiment. Location: Iowa Agricultural Experiment Station, Ames, Iowa

used cover with new polyethylene showed a transmission reduction of 3 to 4 percent. However, continued exposure into May accelerated the transparency degradation. Annual cover replacement would be required. This would represent an annual materials cost, based on 1976 prices, of about \$45, or about 20 percent of the total capital investment cost of \$228 for the collector itself. The predicted life of the suspended collector is estimated to be 5 years. The system's air flow design was for 4,400 cfm (2,200 cfm/section), or an average of 17.19 cfm/ft^2 of surface area.

Drying Performance

The storage facility used in this experiment was a 17-ft high, 18-ft diameter round steel bin. The bin was filled to a depth of about 15.5 ft with 3,440 bu of shelled corn (w.b.) over a 2-day period. The ratio of collector surface to bin volume was 1:13.67 and the ratio of collector surface to bin floor area in this experiment was 1:0.99. The air flow used in the drying process (through the corn) measured 1.28 cfm/bu. The corn averaged 19.8 percent moisture (w.b.) and was dried to 14.4 percent moisture in 44 days.

On some days, it was inoperable due to inclement weather. The operation was interrupted for almost 2 days in early December because of a heavy snowstorm and again for 6 days in March when a severe snow and sleet storm prevented solar drying and stopped all electrical service. For various reasons, the system was not operated for half-day periods at other times.

From the time the drying started on November 27, the dryer fan was used continuously. An electric heater (4.8 kWh) supplemented the solar collector from 7 p.m. to 7 a.m. daily. This management schedule was followed until unfavorable weather conditions permanently halted the fall drying operation on December 19. At that date, the moisture level of the corn was 19.7 percent (w.b.) in the top 5 ft but 15.7 percent 2 ft from the drying floor. From December 30 through March 18, the drying fans were operated 2 hours daily and the solar collector was bypassed. The moisture content of samples taken from the top 5 ft of grain at the end of the winter drying period averaged 20.7 percent while that on the floor averaged 15.4 percent. No evidence of spontaneous heating was observed. Beginning March 19, the fall management schedule resumed. By mid-April, the moisture samples showed that the corn had approached the desired drydown level (14.4 percent). The condition of this corn was uniformly excellent. However, electric consumption was high. In total, 2.6 kWh of electricity per bushel were used during the drying period, or 0.47 kWh/bu per percentage point of moisture removed.

Costs

The suspended plate solar collector system appeared to be low in cost. Total capital investment was $1,664 with only 14 percent of this cost attributed to the collector itself. Unlike the other systems studied, a supplemental electric heater was used and included in the costs. It would not be likely to be used in some years. Conversely, in some years, supplemental heat would be needed with the other collectors studied.

Solar radiation was shown to save 24 percent in energy costs with an adjoining control unit used for comparison. In other words, in removing 5.4 percentage points of moisture, 0.8 kWh/bu or 2 cents/bu, dry basis (d.b.), (at the rate of 2.5 cents/kWh) was saved. Nevertheless, the total consumption of electricity in this experiment appeared to have exceeded the Btus required to reduce the moisture level from 19.8 percent to 14.4 percent. The capital investment cost of this collector amounted to $0.89/ft^2 of surface area. The capital investment cost per square foot of surface area per year of life was estimated at $0.18. Total drying cost per bushel came to an estimated 15.0 cents.

Fixed cost. Fixed cost for the suspended plate system, including the cost of the supplemental electric heater, amounted to 6.6 cents/bu. Dryer depreciation was only 1.2 cents/bu, using an estimated life of 5 years and a 10-percent salvage value. The large volume of corn dried relative to the comparatively small investment cost in this system contributed greatly to a low per unit fixed cost.

Variable cost. Variable cost totaling 8.4 cents was increased by the need to replace annually the 6-mil polyethylene plastic film. Electricity costs were also upped because of the use of supplemental heat. They totaled 1.2 cents per bushel per point of moisture removed. It should be reemphasized that weather conditions during the experiment were not the most favorable and, if it were rerun, the electricity cost could be considerably lower.

Wraparound

System Design

Of the eight solar grain dryers studied, this was one of the three manufactured commercially. It may be considered a second- or third-generation wraparound as the earlier designs were homemade. This collector covered the southern 270° of the bin perimeter, giving it approximately 681 ft^2 of energy absorption surface. [9] However, instead of having two layers of materials as in the earlier designs, this design had only one. The material was a 16-gauge corrugated steel coated with a

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[9] On vertical surfaces where there is little stress applied to the panels, a very lightweight galvanized corrugated roofing, sheet metal, or aluminum may be used, thus reducing the capital investment cost.

black copolymer similar to the coatings used on road culverts. This wraparound was attached to the bin by 4-inch metal spacers and ducted into a central concentration point on the south side of the bin. (Earlier wraparound models used 1-inch by 2-inch wooden spacers to attach the collector to the bin.) A 10-hp fan was housed in an attached enclosure and set on a 7 ft by 10 ft concrete slab (fig. 6).

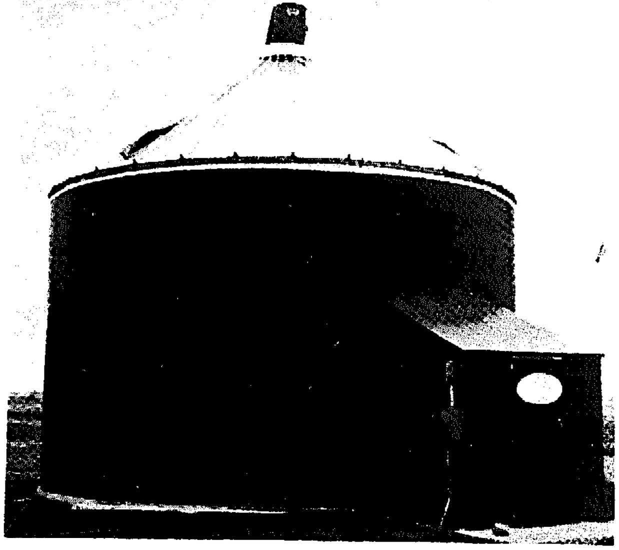

Figure 6
Stationary Wraparound Solar System used in corn drying experiment, located at South Dakota Agricultural Experiment Station, Beresford, South Dakota

Although no supplemental heat was used in 1976, an electric heater was available for use. In this case and others where supplemental heating was planned, electric timers made it possible to switch to supplemental heat for a specified number of hours when solar heat was not available, say from 7:00 p.m. until 7:00 a.m. Cost of the electric heater was not included.

The system's air flow design produced 12,000 cfm or an average of 17.62 cfm/ft^2 of surface area. Air flow was unobstructed by the spacers, an improvement over homemade wraparound designs which used wooden spacers.

Although the wraparound design appears to be an effective means of drying corn, the potential for insect-related problems should be mentioned. Without a means of turning off the heat, the temperature of corn stored in the bin could average quite warm during the storage period, giving rise to insect infestation. Within limits, the rate of development and the reproductive capacity of all grain-infesting insects increases as the temperature increases. A grain temperature of 70° F is considered to be the danger point.

Drying Performance

The storage facility used was a 14-ft high, 23.5-ft diameter round steel bin. The bin was filled to a depth of approximately 6 ft with 1,300 bu of shelled corn (w.b.) in a 1-day period. Because of drought conditions in 1976, this was all the high-moisture corn that could be located for this experiment. (For the cost analysis in this report, it is assumed that four batches of corn could be dried by this system in an 18-day period.) The ratio of collector surface to bin volume was 1:7.34 and the ratio of collector surface to bin floor area was 1:0.64. Given the ratio of collector surface to bin volume, a larger volume could probably have been dried per batch. There is, however, a question of whether a larger volume could have been dried within the constraints of the harvest period. The air flow used in the drying process (through the corn) measured 9.23 cfm/bu. The corn averaged 20.5 percent moisture (w.b.). Drying commenced on November 17 and continued for 4.5 days. The corn was dried to 14.5 percent moisture.

In total, 0.9 kWh of electricity per bushel of corn was used during the drying period, or 0.15 kWh/bu per percentage point of moisture removed. Weather conditions will determine the probability of needing supplemental heat at this and other locations. [10]

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[10] The addition of supplemental electric or fossil fuel grain dryers as backup machinery for use at night or in inclement weather is within the realm of good farm management practices.

When more heat is needed, fuel usage will of course be greater.

Costs

Because this was a commercial experimental model, much time and expense were involved in design including the construction of a mini-model. The $1,900 capital investment cost used in this report is an estimation assuming limited mass production, rather than the actual cost of this collector. 11/ Cost of the 10-hp fan and transition duct totaled an additional $1,193. The electrical hookup charge was $400, the same as for all other collectors. Because of the durability of this system, no fencing was needed. This, in turn, minimized the land (space) charge to the area occupied by the bin and fan house, which was estimated at $11. Thus, the total capital investment cost estimate for this collector amounted to $3,504. The capital investment cost per square foot of collector surface totaled $2.79. The capital investment cost per square foot of collector surface per year of life was estimated at a low 14 cents, low because of the collector's long life expectancy. Total drying cost per bushel was estimated at 10.3 cents.

Fixed cost. Because of the durability of this system, it was the only one studied that would not require a fence for protection from livestock. Its life expectancy was estimated at 20 years with a salvage value of 10 percent. If 4,200 bushels of corn had been dried (full capacity), dryer depreciation would have been 1.6 cents and interest on investment 2.6 cents/bu. 12/ 13/ Total fixed cost per bushel would have been an estimated 7.8 cents.

Variable cost. Total variable cost for this commercially built wraparound unit came to 2.5 cents. Repair costs, because of the durable construction, were estimated to be only 0.3 cent/bu. (Although the repair costs of this and other systems would be expected to increase with added use, they would likely be lower for larger capacity dryers.) The electricity cost was 2.2 cents/bu, or 0.37 cent/bu per percentage point of moisture removed.

Intensifier

System Design

This collector was designed, as the name implies, to intensify the sun's rays. A 12-ft by 36-ft "billboard" type structure (slightly concave to the collector) reflected the sun's rays in a narrow band, about 24 to 30 inches wide, upon the collector itself. The intensifier was located about 12 ft to the north of the collector and faced south. It was constructed of masonite hardboard with a polished aluminum adhesive used as the reflective material.

The vertical collector is illustrated in figure 7. Its dimensions were 4 ft by 24 ft. It was constructed primarily of dimension lumber, galvanized steel, and plastic. In the center of

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11/ It may be possible, with mass production, to lower the commercial cost to $1,500 or lower, f.o.b. manufacturer. Also, it should be noted that engineers estimate a similar design can be homemade for approximately one-third this cost.

12/ This system was equipped with an unloading device that would make it entirely possible for grain transfer to a storage bin.

13/ In some cases it may be feasible to spread fixed costs over more than one binful of corn within a year's period of time, as well as over more than one grain.

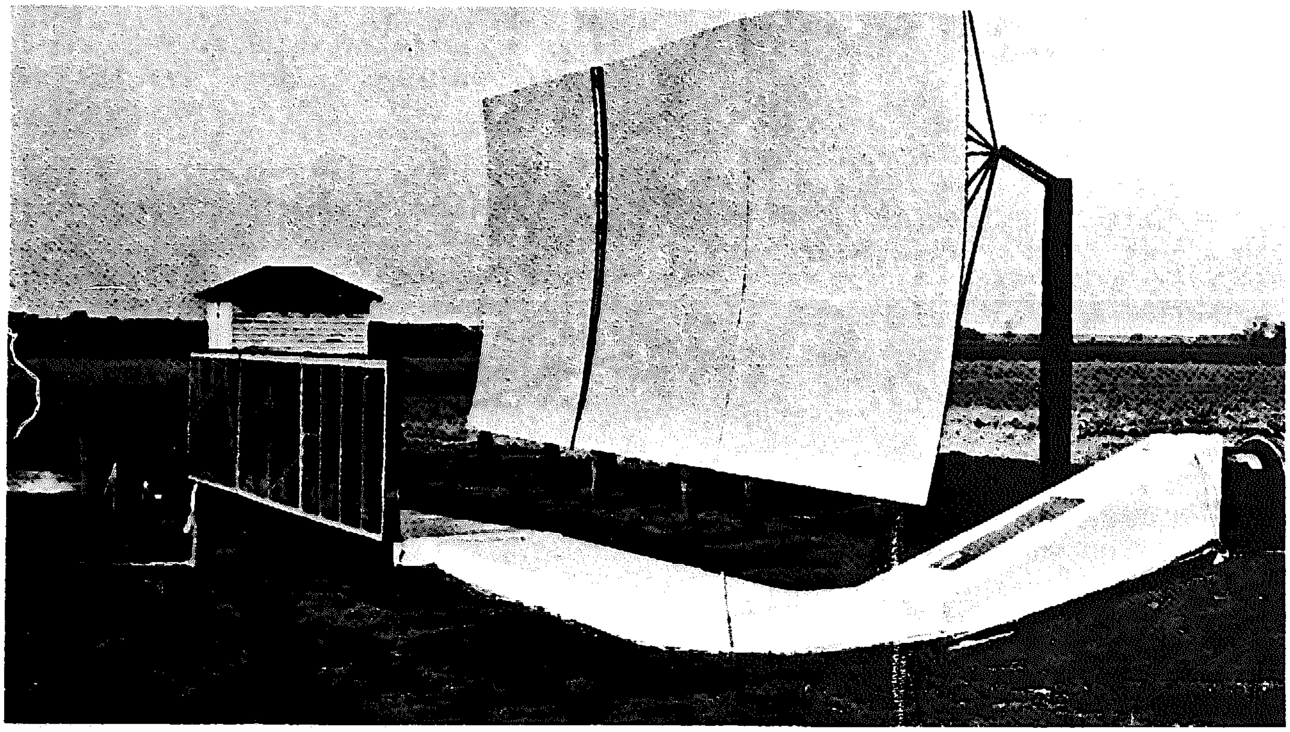

Figure 7
Stationary Intensifier Solar System used in corn drying experiment. Location: South Dakota Agricultural Experiment Station, Brookings, South Dakota

the collector, there was a panel of 28-gauge corrugated roofing steel. Next, about 1 inch on either side of the collector were panels of 3-mil polyester film. Finally, a layer of laminated polyester and acrylic plastic film 3/4 inch beyond the polyester film served as the surface cover. The purpose of the laminated plastic was for strength (polyester) and longevity (acrylic). Even with these properties, care had to be taken to insure that the fan was activated on sunny days or that the intensifier was tilted back to prevent the intensifier from causing heat to build up to the point of melting the plastic. The tilting device also allowed seasonal adjustment of the reflected energy onto the collector.

The intensifier system was designed to capture solar energy from 9 a.m. to 3 p.m. Collectors must be designed differently in northern latitudes than in southern latitudes to capture the sun's rays. In the northern latitudes, horizontal collectors are at a disadvantage over vertical ones such as the intensifier because of the sun's position in the fall months. A concentration ratio of 4:1 on the collector surface was the design objective, giving the unit an equivalent of 384 ft^2 of collector surface.

A heat duct was built on the ground at the base of the vertical collector. It was connected to a 3-hp, 18-inch electric fan by a transition duct. The air flow design produced 2,000 cfm, or an average of 5.21 cfm/ft^2 of surface area.

Drying Performance

The storage facility used in this experiment was a 9-ft high, 18-ft diameter round steel bin with a capacity of approximately 1,400 bu. The bin was filled to a depth of approximately 8 ft with 1,300 bu of shelled corn (w.b.) in a 2-day period. The ratio of collector surface to bin volume was 1:3.65 and the ratio of collector surface to bin floor area in this experiment was 1:0.66. Air (1,000 cfm) was drawn into the solar collector along the bottom of the 24-ft long collector. It flowed vertically up the 4-ft height on the south side and down on the north side. It was then collected in an insulated plenum, mixed with an equal volume of unheated air, and forced into the conventional, false-floor drying bin. An additional 1,000 cfm of outside air was pulled in through the fan, with the result that air at a temperature of 78° F was forced through the grain. 14/ The air flow used in the drying process (through the corn) measured 1.54 cfm/bu. The corn initially averaged 32.8 percent moisture (w.b.). Drying started on November 8 and was continued for 22 days. The corn was dried to 16.4 percent moisture.

For this collector, a total of 2.28 kWh of electricity per bushel were required during the drying period, or 0.09 kWh/bu per percentage point of moisture removed. No supplemental heat was used.

Costs

Together, the intensifier and the vertical collector capital investment cost totaled $1,405, or 57 percent of the investment in the entire dryer complement. Capital investment costs of the two structures, per square foot of effective surface area, totaled $3.66. The capital investment cost per square foot of surface area per year of life was estimated to be $0.37. Total drying cost per bushel was estimated at 33.5 cents.

Fixed cost. The life expectancy of this collector was 10 years with a 10-percent salvage value. The collector and reflector systems were designed to withstand an 80-mph wind. The probability of a wind of this velocity occurring in the location of this experiment is one in 50 years. Thus the basic structure was quite durable and the necessity of this strength to withstand severe winds is reflected in the capital investment cost. Total fixed cost per bushel came to 26.6 cents. Collector depreciation costs alone accounted for about one-third of this total.

Variable cost. Variable costs totaled 6.9 cents/bu for the intensifier system. Repairs and maintenance costs were 3.1 cents/bu. An estimated 13.5 kWh of electricity were used per 100 pounds of water removed. At 1.75 cents/kWh, the cost per bushel was 3.7 cents. The electricity cost per bushel per percentage point of moisture removed was 0.22 cent.

Air-Supported

System Design

The air-supported collector was essentially a quasi-suspended plate collector with a high crown and curved cover (fig.8). It was mounted horizontally on the ground and operated like the inflated tube collector previously described. The air-supported collector was 80 ft long, 12 ft wide, and 4 ft high when inflated. Its solar collection surface was estimated at 960 ft^2 This collector was constructed with three layers of 10-mil vinyl UV stabilized plastic sheets. The outer layer was clear, the middle layer translu-

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14/ This temperature varied throughout the experiment.

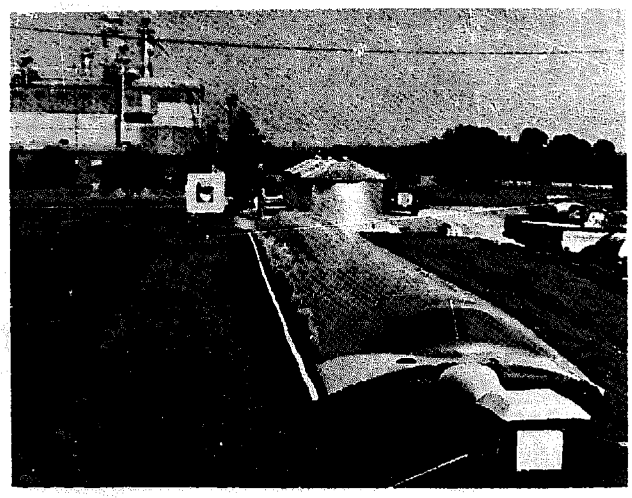

Figure 8
Stationary Air Supported Solar System used in corn drying experiment. Location: Ohio Agricultural Experiment Station, Wooster, Ohio

cent, and the inner layer, opaque. The collector was anchored with metal screw-type eye-augers and nylon rope. A 1/2-hp centrifugal electric fan located at the inlet end inflated the collector and delivered air predominantly between the bottom two layers of plastic. The solar heated air was forced into the grain by a 3-hp, three-phase motor electric fan which was located next to the bin. The duct system was designed so that the bin fan could be operated to aerate the grain when no solar heat was being collected, thus allowing for a 24-hour-a-day drying-aeration operation.

Because of the thickness of the plastic, the air-supported collector's durability exceeded that of the inflated tube collector. The former's life expectancy was estimated to be 6 years, assuming it is put up, used approximately 2 months, and taken down each year. Total labor for putting it up and taking it down was estimated at 16 hours per year. The system's air flow design required a minimum of 1,800 cfm, or 1.88 cfm/ft^2 of surface area.

Drying Performance

The storage facility used in this experiment was a 14-ft high, 30-ft diameter round steel bin with a filled capacity of approximately 8,000 bu. The bin was filled to a depth of about 3 ft with 1,680 bu of shelled corn (w.b.). The ratio of collector surface to bin volume was 1:8.33 and the ratio of collector surface to bin floor area was 1:0.47. The air flow used in the drying process (through the corn) measured 1.07 cfm/bu. Four batches of corn, or a total of 6,720 bu, were dried during the fall season, at approximately 6 days per batch. 15/ The corn initially averaged 20.9 percent moisture and was dried to 15.2 percent moisture.

A total of 5,040 kWh of electricity were used to deliver solar heat into the bin. Per bushel, 0.75 kWh of electricity was used by this system, or 0.13 kWh/bu per percentage point of moisture removed.

Costs

This collector was produced commercially, as was the wraparound collector. Capital investment cost of the original unit may be slightly greater than for future collectors of the same design. An estimated cost of $2,000 for the collector itself was used in this analysis. At this acquisition cost, the capital investment cost per square foot of collector surface came to $2.08, and per square foot of collector area per year of life it was estimated at $0.35. The capital investment cost of the collector itself represented two-thirds of the initial investment costs. Total drying cost per bushel amounted to 12.8 cents.

Fixed cost. Because of the large ratio of collector surface to bin capacity, this system was capable of drying a large volume of corn. Four batches of corn could be placed in the storage bins for drying within the time constraints of a normal harvest period.

15/ Even if 10 percentage points of moisture had been removed from the corn, four batches could have been handled with this system.

As a result, fixed costs were 9.1 cents/bu. With the estimated 6-year life and a 10-percent salvage value, system depreciation costs were 4.5 cents, or about one-third of the fixed cost.

Variable cost. Total variable cost of this system came to 3.7 cents, mainly for fuel and repairs. Electricity cost 1.9 cents/bu, or 0.3 cent/bu per percentage point of moisture removed. Annual repairs, including putting the collector up and taking it down, were 1.7 cents/bu.

Multiuse

System Design

Two objectives, 24-hour heat and 12-month utilization, led to the design of this system. The basic design included a portable flat-plate collector mounted on a trailer, a rock heat-storage bin, and a thermostatically controlled air handler (fig. 9). The commercially built collector was 6-1/2 ft by 12 ft. It had a solar collection surface of only 78 ft^2. The frame was of steel construction and the material used for the cover plate consisted of two 1/8-inch double-strength tempered glasses spaced 1 inch apart so as to form a thermopane. These were in a series of 4 panels, each 3 ft by 6-1/2 ft. The absorber surface was sheet-metal, and the outer surface was coated with a flat black paint. Another flat metal plate was spaced 1/2 inch below the absorber plate, and under the flat plate was a 2-inch bonded fiberglass insulation. The entire collector was tiltable for solar orientation. The collector was bolted to the trailer and, in turn, the trailer was anchored to the ground to prevent the wind from blowing it over.

The ductwork connecting the collector and the fan was a commercial flexible duct made of fiberglass bonded vinyl and a coiled wire frame. A 10-inch, 1/6-hp fan produced a maximum air flow of 300 cfm from the collector. (While this was a relatively small

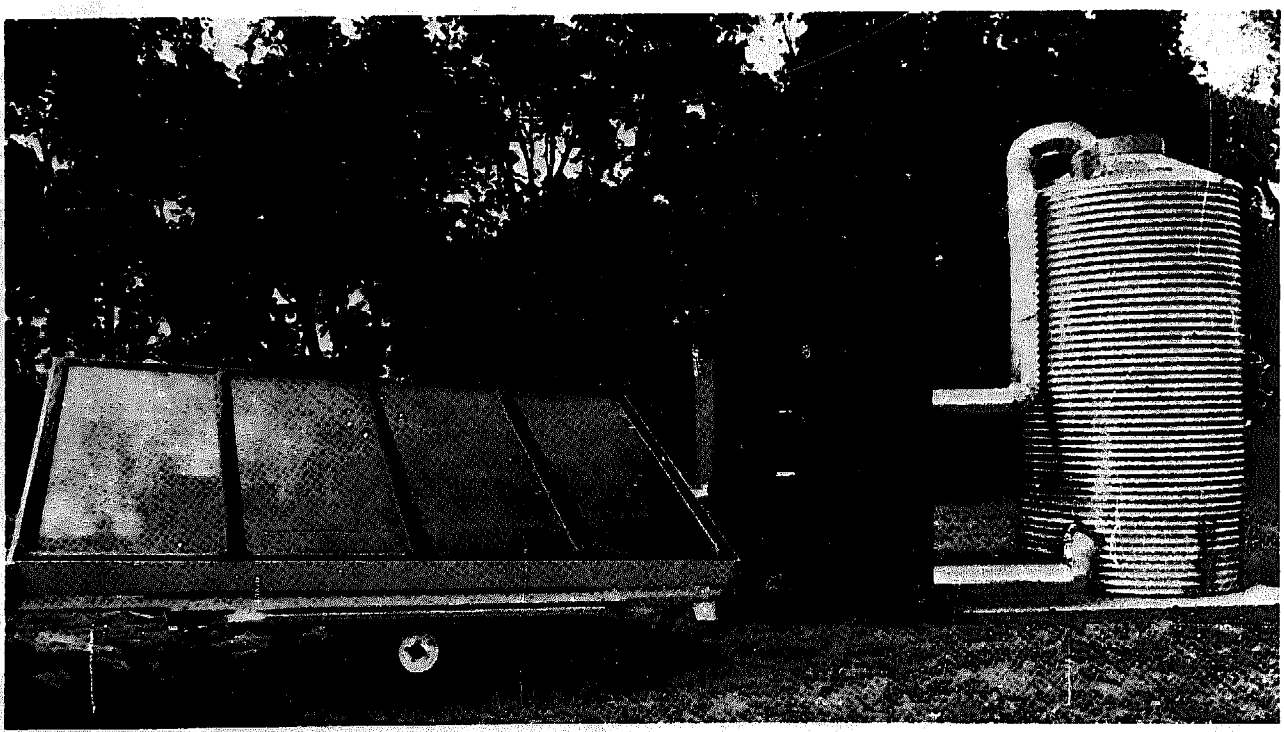

Figure 9
Portable Multiuse Solar System used in corn drying experiment. Location: Engineering Research Center, Colorado State University, Fort Collins, Colorado

experimental model compared with the others studied, the system could be built to handle 5,000 to 10,000 bu of shelled corn.)

This system was designed so that heat from the warm air which was exhausted from the corn could be stored in a permanent rock heat-storage bin located near the grain. The temperature of this air measured approximately 80° to 100° F. An automatic damper in the air handler reversed this air flow and pulled the heat from the rock bin back through the grain to provide heat for nighttime drying. The system's air flow design produced 300 cfm, or an average of 3.85 cfm/ft^2 of surface area.

Drying Performance

The storage facility was a 10-ft high, 6-ft diameter round steel bin with a capacity of approximately 150 bu. The bin was filled to a depth of approximately 8 ft with 130 bu of shelled corn (w.b.) for each batch. The ratio of collector surface to bin volume was 1:1.92, and the ratio of collector surface to bin floor area in this experiment was 1:0.36. The average air flow used in the drying process (through the corn) for two batches was 2.31 cfm/bu. The corn averaged 25.5 percent moisture (w.b.) and was dried to 15 percent moisture in 37 days. Drying of the first batch was started on October 20 and completed on November 3. The air flow rate measured 3 cfm/bu. Drying of the second batch was started on November 15 and completed on December 6. The air flow used in the second batch measured 2 cfm/bu. (The latter batch, higher in initial moisture content, accounted for 21 days of the total drying time.)

In total, 2.28 kWh of electricity per bushel were used for drying, or 0.22 kWh/bu per percentage point of moisture removed. No supplemental heat was used.

Costs

Total capital investment was estimated at $2,337; the collector, including the trailer, flexible duct, and fan, accounted for about 58 percent. However, since the collector itself, the trailer, flexible duct, and fan were used to dry grain for only 2 months or less, the collector actually accounted for only about 10 percent of the grain drying costs. The capital investment cost of the collector totaled $12.82 per ft^2 of surface area. The capital investment cost per square foot of surface area per year of life amounted to $0.64. Total dryer cost per bushel was 18.5 cents.

Fixed cost. The life expectancy of this collector was 20 years, with a 10-percent salvage value. The relatively high life expectancy reduced the depreciation cost, even though the initial capital investment was high relative to the volume that could be dried in one crop year. Collector depreciation, including the flat-plate collector, the trailer, and the rock storage bin was 3.7 cents/bu, or 21 percent of total fixed cost. The charge for the flat-plate collector, excluding the heat-storage bin, came to 2.9 cents/bu, or 17 percent of total fixed cost. It should be noted that only one-sixth of the total fixed costs of this system were charged to the grain drying function.

Variable cost. Total variable cost was 1.5 cents/bu. The cost of electricity (at the rate of 4.0 cents/kWh) amounted to 1.3 cents/bu, or 0.13 cent/bu per percentage point of moisture removed. Total variable cost per bushel per percent of moisture removed was only 0.1 cent for this system.

RANGE IN COST OF SOLAR GRAIN DRYING SYSTEMS

The cost of the eight experimental systems varied greatly in terms of total costs and, in most cases, by cost item (table 6). The difference between the lowest and highest total fixed cost was 20 cents/bu. For variable costs, the range was 6.9 cents. As explained

Table 6--Range of experimental solar grain drying cost estimates and comparison of two solar grain drying systems with two conventional systems, 40,000-bu capacity, 1976

Cost item	Range of experimental solar grain drying costs 1/	Solar		Conventional	
		Flat-plate system 2/	Wraparound system 2/	Continuous flow dryer 3/	Automatic batch dryer 4/
		Cents/bu			
Fixed:					
Dryer depreciation	1.2 - 9.7	5.3	1.7	5.4	3.9
Equipment depreciation	0.5 - 3.0	1.6	1.6	0.4	0.4
Electricity hookup	.3 - 1.5	5/	5/	5/	5/
Insurance on dryer and equipment	.2 - 0.9	0.3	0.4	.3	.2
Interest on investment	2.0 - 7.9	2.6	2.8	2.2	1.6
Taxes (personal property or real estate)	.9 - 3.6	1.2	1.4	1.0	.8
Subtotal	6.6 - 26.6	11.0	7.9	9.3	6.9
Variable: 6/					
Direct labor	7/ - 7/	.3	.2	.5	.5
Electricity	1.3 - 6.4	3.2	2.3	.1	.1
LPG	8/ - 8/	8/	8/	4.3	4.0
Repairs and maintenance	.2 - 3.2	2.0	.3	1.1	.8
Interest on working capital	.0 - .2	.1	5/	.1	.1
Subtotal	1.5 - 8.4	5.6	2.8	6.1	5.5
Total cost	10.3 - 33.5	16.6	10.7	15.4	12.4

1/ See table 5.

2/ Duplicate collectors are used to handle a 40,000-bu volume.

3/ Capacity of 180 bu/hour.

4/ Maximum daily filling rate for corn is 2,500 bu.

5/ Less than 0.1 cent.

6/ Charges for insurance and taxes on grain were omitted under the assumption that these costs are associated with the storage function rather than the drying function.

7/ Direct labor was omitted from experimental solar drying cost estimates because the only labor required was to measure moisture content of grain. If an assumption of a given amount of labor per day is made, the small-volume experiments are unjustly penalized.

8/ Not applicable.

previously, such factors as differing amounts of moisture removed and different electricity rates preclude direct comparison of these experimental systems. Thus, these ranges are pointed out to show that if costs differ there is a good chance that the higher costs can be lowered by some change in design.

The range in fixed costs was largely related to (1) the volume of corn dried, (2) original capital investment, and (3) estimated life of the collector. The first of these factors was, of course, related to the utilization of capacity while the latter two were more related to the selection of construction materials. The capital investment cost of the eight solar collectors studied ranged from \$0.89 to \$12.82 per ft^2 of collector surface. The collectors with longer life expectancy were not always the least-cost systems. The type of construction materials and the efficiency of the overall design appeared to be the major factors affecting the capital investment per ft^2 of collector surface per year of estimated life. At this point, it would appear economically possible to construct a well-built, homemade collector for between \$1 and \$2 per ft^2 of collector surface. However, the best investment may be a commercial collector selling for between \$3 and \$6 per ft^2 of collector surface as this collector has a longer life expectancy than do homemade ones.

The reduction of variable costs is important although the potential may not be as great as for lowering fixed costs. As the efficiency of solar collectors is improved and as less expensive or more durable construction materials are used, electricity and repair costs may also be lowered. The real necessity for lowering variable costs, however, is related to the energy situation and the need for conserving electricity as well as fossil fuels.

Also, solar collectors are susceptible to damage or disrepair just as conventional dryers are susceptible to mechanical breakdowns. However, the cost of repairs and maintenance of solar collectors should be lowered as more durable materials are used and as better management practices are learned. Given the current state of these systems, the range in repair costs was greater than for any other cost item (table 6). This, of course, is related to the extremes in construction--low-cost homemade collectors vs. high-cost commercial collectors. Low-cost collectors generally have high repair and maintenance costs while commercial ones do not.

Costs of some of the eight experimental models are as low as or lower than some of the conventional drying methods. This conclusion is particularly significant at this stage of the technological knowhow because certain avenues for lowering costs have not been explored. For example, in only one case, the multiuse collector, was the idea of alternative uses considered.

Another possible method of reducing costs of solar grain drying is through cost efficiencies associated with larger collectors. At this stage, economies of size have not been addressed; most of the experimental models can best be described as minisystems, or scale models. The issue of economies of size should be researched to test quality control as well as economy because little is known about the performance of solar grain drying systems under field conditions. It is important to design or simulate performance of systems adequate in size to serve farms producing 25,000 to 50,000 bu of corn or more. Otherwise, it is impossible to assess adequately the feasibility of solar drying on a commercial scale. There are, in addition to the economic and size considerations, a host of technological assessments that need examination. These relate primarily to the role of solar drying in farmstead layout, speed of harvest, off-farm corn sales strategies, and financing.

COST COMPARISONS BETWEEN SOLAR AND CONVENTIONAL GRAIN DRYING SYSTEMS

The costs of the flat-plate system (a medium-cost solar dryer studied) and the wraparound system (the lowest-cost solar dryer studied) were compared with those of a high-temperature continuous-flow dryer and an automatic batch dryer, both fueled with LPG. The economic feasibility of one large solar dryer is unknown at this time; thus, eight 5,000-bu unit dryers in each of the two experimental systems were used to estimate costs of drying 40,000 bu of 25-percent moisture corn. Costs of the conventional dryers were also based on 40,000 bu. Drying period was set as approximately 18 12-hour days. 16/

Total costs per bushel for the wraparound solar drying system were less than for the conventional dryers, primarily because of the savings in fuel costs. Depreciation costs were also considerably lower (see table 6, In contrast, the total costs for the flat-plate solar drying system were from 1.2 to 4.2 cents/bu higher than for the conventional dryers. Variable costs for the flat-plate solar grain-drying system were within the range of those of the conventional dryers but fixed costs were higher.

Under the assumptions used (see the appendix), labor requirements were estimated to be slightly lower for the solar drying systems. As these systems are further tested, this cost item could perhaps be reduced more because of the use of larger volume bins. In the comparisons made in this study, more time was assumed necessary to check grain quality in eight small bins than in one or two large bins.

A major tradeoff when considering a solar grain drying system is between the use of electricity and the use of LPG or natural gas. For solar drying, electric energy is needed only to operate fans to circulate solar heat. Engineers are still experimenting with the optimal size for fans and with other problems associated with the efficiency of solar energy collection and use. Currently, however, it seems that the electricity needed to run a dryer fan alone can be kept below 1 kWh/bu/10 percentage points of moisture removed. This is equivalent to less than 3,400 Btu/bu/10 percentage points of moisture removed. In comparison, about 6,930 Btu of LPG (approximately 0.1 gal), as well as a small amount of electricity, would be needed to remove the same amount of moisture. In terms of fuel costs (table 6) well over half the variable costs of the conventional dryers were attributed to LPG. This finding is significant not only from the standpoint of cost, but also from the standpoint of diminishing energy supplies.

In summary, it appears 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. However, before wide-scale adoption takes place certain technological aspects remain to be sorted out. It is still uncertain just how much moisture can be safely removed from corn without quality deterioration, and, in turn, how well solar collectors perform in certain climates when high-moisture corn (over 25 percent) needs to be dried. 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.

16/ Even for proven large-scale drying-storage systems, there is an economic tradeoff between economies of size (large bins) and the flexibility of using two or more smaller bins. However, while the costs of these dryers were similar, the required number of small bins for the two solar-powered systems would cost about twice as much as the two or three large bins for a continuous flow drying system. As further research is conducted, it may be found that there are economies of size, or it may be found that it is not feasible to dry corn in large volume increments using low to medium temperatures.

Also, little is known about a potential insect problem that may be associated with solar drying. Because exterior walls of some bins are black, temperature of the grain stored within could exceed 70° F for longer periods of time than would occur if the walls were a different color. This increases the chance for infestation by insects that attack stored grain. 17/

When comparing solar drying costs with those of conventional fuel dryers, it is important to distinguish between total solar drying and combination solar-aeration or solar-supplemented electric heat drying. The use of electricity, either for fan operation or heat, quickly adds to the total cost. This points out the need to establish the boundaries of a feasible or effective solar grain drying belt where grain can be dried, with a high degree of reliability, using solar energy as near to 10 years out of 10 as possible. Once such an area is determined, more effective research can be conducted and more useful research recommendations can be made.

ESTIMATED FUEL SAVINGS

Estimated energy contribution of the experimental solar grain drying systems (in Btu) and their economic savings over use of conventional fuels are shown in table 7. Cost savings are greatest when the solar systems are compared with an all-electric heat drying system, and least when they are compared with a natural gas heat system. The payout 18/ for each solar system in fuel savings alone can be determined by comparing the savings shown in table 7 with the capital investments in table 3. The flat-plate collector, for example, supplied 42 million Btu of the 54 million required to remove 30,227 lb of water. The savings over natural gas use would have been $50.03 for the 5,029 bu dried. The payout period for this system in fuel savings would be 63 years [$3,174 (total capital investment)] ÷ [$50.03 (economic savings resulting from use of solar energy instead of natural gas)]. Corresponding payout periods for systems using the more expensive fuels, LPG and electricity, would be about 25 and 5 years, respectively. Fuel savings in the case of the wraparound collector were less, making the payout period for that collector even longer. Thus, if considering fuel savings only, it can be concluded that neither collector is economically feasible. The payout is not short enough. However, as fuel prices increase the payout period will decrease and at some point in time it may be economically feasible for farmers to replace operable conventional dryers.

It should also be pointed out that most collectors' surface materials are made of synthetic products derived from fossil fuels. Thus, they may be expected to increase in cost at about the same rate as the fuel itself, which partially offsets any economic advantages of solar collectors. Experiments are underway using materials not derived from fossil fuels, such as glass, for collector surfaces.

FUTURE ENERGY COSTS

The U.S. grain handling system evolved as it is today with abundant supplies of low-cost energy. Now, however, future energy availability and energy costs are significant concerns. Immediate concerns with energy conservation have prompted research on the feasibility of solar energy and other alternative forms.

In the long run, shortages of conventional crop drying fuels may make alternative methods of grain drying or harvesting practices mandatory. In the short run, increasing fuel costs will make the adoption of new methods and practices more desirable. In certain parts of the Corn Belt and Great Plains, solar grain drying may be feasible; in

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17/ See R.T. Cotton, et al. Causes of Outbreaks of Stored-grain Insects. Bul. 416, Kans. Agr. Exp. Sta., Feb. 1960.

18/ The payout is the period of time required for accumulated savings to equal initial investment.

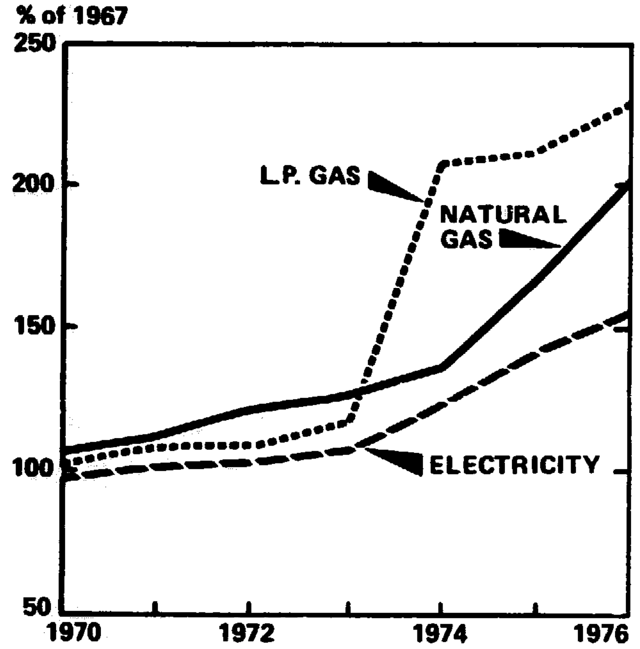
Table 7--Energy contributed by solar grain drying systems and economic savings over conventional fuels, eight selected systems, 1976

Type of collector	Water loss	Energy requirement 1/	kWh used	Energy used 2/	Solar energy	Annual economic savings over		
						All electric 3/	LPG 4/	Natural gas 5/
	Pounds	1,000 Btu	Number	---1,000 Btu---		- - - - -	Dollars	- - - - -
Rock heat-storage	7,788	14,018.4	462	1,576.8	12,441.6	102.55	23.31	10.99
Flat-plate	30,227	54,409.6	3,538	12,075.2	42,333.4	558.80	127.00	50.03
Inflated tube	11,630	20,934.0	468	1,597.3	19,336.7	255.24	58.00	25.14
Suspended plate	12,153	21,875.4	8,783	6/29,976.4				
Wraparound	18,732	33,717.6	4,680	15,972.8	17,744.8	234.23	53.23	23.07
Intensifier	23,400	42,120.0	1,936	6,607.6	35,512.4	468.76	106.54	46.17
Air-supported	25,295	45,531.0	5,040	39,106.2	6,424.8	84.81	19.27	8.35
Multiuse	1,799	3,238.2	228	778.2	2,460.0	32.47	7.38	3.20

1/ 1,800 Btu required to evaporate 1 lb of H_2O with 66-2/3 percent heat utilization.
2/ 3,413 Btu/kWh.
3/ Estimated price. $0.0132 per 1,000 Btu (electricity rate of 4.5¢/kWh).
4/ Estimated price. $0.0030 per 1,000 Btu (propane rate of 27.0¢/gal).
5/ Estimated price. $0.0013 per 1,000 Btu (natural gas rate of 0.13¢/ft^3).
6/ Use of electricity exceeded the amount necessary to remove water without solar heat. (In this experiment, inclement weather was encountered and supplemental electric heat was used.)

other regions, it may not. Widespread adoption of solar drying will depend on at least three factors: (1) the economic feasibility, (2) the geographical area in which the climate favors solar drying, and (3) the design of a system large enough to be practical on commercial farms. Additional research is needed in all three areas. Nevertheless, this study shows that, today, the costs of efficient solar grain drying systems are reasonably close to those of some conventional drying methods (table 6) and that there may be ways of further reducing solar costs as more efficient and larger systems are designed. Fortunately, solar drying systems do appear to offer an alternative drying method, at approximately the same overall cost, which could be used in some years and at least in some corn producing areas either in the absence of fossil fuels or if fossil fuel prices become prohibitive.

Electricity, the only fuel used by the eight solar drying systems studied, increased less in price per unit than did natural gas or LPG from 1970 to 1976 (fig. 10). Prices of both natural gas and LPG have doubled since 1970. If the pattern of fuel prices continues to change as it has in recent years (fig. 10), several of the experimental solar dryers included in this study, as well as others, may become economically feasible. At any rate, the economic feasibility of solar grain drying appears promising enough to warrant continued research to enhance (or further improve) solar drying technology.



Source: L.P. Gas and Electricity: Prices Paid by Farmers, Agricultural Prices, Statistical Reporting Service, U.S. Department of Agriculture. Natural Gas: Residential Retail Prices, U.S. Bureau of Labor Statistics. (Based on U.S. average prices)

Figure 10
Price changes of alternative crop drying fuels

The economic feasibility of solar grain drying systems is largely related to savings in the areas of fuel and investment cost over the costs of conventional drying systems. Fuel costs especially are likely to continue to rise in the coming years and, as they do, the economic advantages of solar systems will increase. Assuming an annual cost increase of 5 percent for both electricity and natural gas, the flat-plate system would gain a 4-cent advantage over the continuous flow dryer and a 1.5-cent advantage over the automatic batch dryer in 20 years. In comparison the wraparound system should gain an advantage of 11.5 cents compared with the continuous flow dryer and 9 cents compared with the automatic batch dryer, over a 20-year period.

To aid the producer in decision-making, length of time to reach payout was computed for the wraparound solar drying system (table 8). Since payout is related to use, a range of capacity utilization from 30 percent to 210 percent was assumed. In other words, at the 210-percent level, better than two full batches of corn are assumed to be dried during the year. The maximum utilization level would appear feasible according to the experimental results of the wraparound system.

Capital for the payouts shown in table 8 includes depreciation, interest on investment, and savings (fuel or other) for solar drying, if any. The sum of these items was divided into the capital investment, $3,504, to yield payout in years.

Depending on the use rate and the assumed savings, the payout period for the wraparound system ranges from about 12 years down to about 6. If used

Table 8--Estimated length of time required to reach payout for wraparound solar grain drying system

Savings per bushel	Use rate (percent) and annual volume (bu)						
	30 1,500	60 3,000	90 4,500	120 6,000	150 7,500	180 9,000	210 10,500
Cents	Payout in years 1/						
0	11.9	11.9	11.9	11.9	11.9	11.9	11.9
1	11.3	10.8	10.3	9.9	9.5	9.1	8.8
2	10.8	10.3	9.9	9.5	9.1	8.8	8.4
3	10.3	9.9	9.5	9.1	8.8	8.4	8.1
4	9.9	9.5	9.1	8.8	8.4	8.1	7.9
5	9.5	9.1	8.8	8.4	8.1	7.9	7.6
6	9.1	8.8	8.4	8.1	7.9	7.6	7.4
7	8.8	8.4	8.1	7.9	7.6	7.4	7.2
8	8.4	8.1	7.9	7.6	7.4	7.2	6.9
9	8.1	7.9	7.6	7.4	7.2	6.9	6.7
10	7.9	7.6	7.4	7.2	6.9	6.7	6.6
11	7.6	7.4	7.2	6.9	6.7	6.6	6.4
12	7.4	7.2	6.9	6.7	6.6	6.4	6.2

1/ Total investment outlay ($3,504) divided by depreciation ($160) plus interest on investment ($135) plus savings, if any.

at 30 percent of capacity, an estimated 10-cent savings resulted in a payout period 4 years shorter than if there were no savings in a solar system versus a conventional system. However, at the 210-percent use rate, the payout decreases from about 12 years assuming no savings down to about 6.6 years assuming a 10-cent-per-bushel savings.

APPENDIX: Derivation of costs for comparisons of two solar dryers and two conventional dryers

Flat-plate solar drying systems drying 40,000 bu
(eight 5,000-bu systems duplicated)

Fixed cost per bushel

Collector depreciation:

$$\frac{\text{Original cost (\$1,482) - 10\% salvage value (\$148)}}{\text{Life (5 years)}} = \text{\$267 x 8 (duplicates) = \$2,136} \div$$

40,000 bu = 5.3¢

Equipment depreciation:

$$\frac{\text{Original cost (\$1,170) - no salvage value}}{\text{Life (15 years)}} = \text{\$78 x 8 (duplicates) = \$624} \div \text{40,000 bu = 1.6¢}$$

Electrical hookup:

$$\frac{\text{Original cost (\$400) - no salvage value}}{\text{Life (20 years)}} = \text{\$20 x 8 (duplicates) = \$160} \div \text{40,000 bu = 0.04¢}$$

Insurance on dryer and equipment:

Original cost of collector ($1,482) + original cost of equipment ($1,170) = $2,652 x $6/$1,000 = $16 x 8 (duplicates) = $128 ÷ 40,000 bu = 0.3¢

Interest on investment:

Original cost of collector ($1,482) + original cost of equipment ($1,170) + original cost of electrical hookup ($400) + original cost of fencing ($89) = $3,141 ÷ 2 = average value ($1,570) + land value ($33) = $1,603 x interest charge (8%) = $128 x 8 (duplicates) = $1,024 ÷ 40,000 bu = 2.6¢

Taxes:

Original cost of collector ($1,482) + original cost of equipment ($1,170) + original cost of electrical hookup ($400) = $3,052 x assessment (30%) = $916 x 65 mills = $60 x 8 (duplicates) = $480 ÷ 40,000 bu = 1.2¢

Variable cost per bushel

Direct labor:

22 days of drying time. Drying operation checked twice daily. Time requirement 15 minutes/bin x 8 bins = 2 hours/day x 22 days = 44 hours x wage rate per hour ($2.50) = $110 ÷ 40,000 bu = 0.3¢

Electricity:

3,538 kWh x 8 (duplicates) = 28,304 kWh x 4.5¢/kWh = $1,274 ÷ 40,000 bu = 3.2¢

Repairs and maintenance:

Estimated annual repairs ($102) x 8 (duplicates) = $816 ÷ 40,000 bu = 2.0¢

Insurance on corn:

At rate of $3.60/$1,000 value/6 months or 0.9¢/bu with corn valued at $2.50/bu

Interest on working capital:

Direct labor (0.5¢) + electricity (3.2¢) + repairs and maintenance (2.1¢) + insurance (0.9¢) = 6.7¢ x 8% = .536¢ ÷ 4 (borrowed for 3 months) = 0.1¢

Wraparound solar drying systems drying 40,00 bu
(eight 5,000-bu systems duplicated)

Fixed cost per bushel

Collector depreciation:

$\frac{\text{Original cost (\$1,900) - 10\% salvage value (\$190)}}{\text{Life (20 years)}}$ = \$86 x 8 (duplicates) = \$688 ÷ 40,000 bu = 1.7¢

Equipment depreciation:

$\frac{\text{Original cost (\$1,193) - no salvage value}}{\text{Life (15 years)}}$ = \$80 x 8 (duplicates) = \$640 ÷ 40,000 bu = 1.6¢

Electrical hookup:

$\frac{\text{Original cost (\$400) - no salvage value}}{\text{Life (20 years)}}$ = \$20 x 8 (duplicates) = \$160 ÷ 40,000 bu = less than 0.1 cent.

Insurance on dryer and equipment:

Original cost ($1,900) + original cost of equipment ($1,193) = $3,093 x $6/$1,000 = $19 x 8 (duplicates) = $152 ÷ 40,000 bu = 0.4¢

Interest on investment:

Original cost of collector ($1,900) + original cost of equipment ($1,193) + original cost of electrical hookup ($400) = $3,493 ÷ 2 = average value ($1,746) + land value ($11) = $1,757 x interest charge (8%) = $141 x 8 (duplicates) = $1,128 ÷ 40,000 bu = 2.8¢

Taxes:

Original cost of collector ($1,900) + original cost of equipment ($1,193) + original cost of electrical hookup ($400) = $3,493 x assessment (30%) = $1,048 x 6 mills = $68 x 8 (duplicates) = $544 ÷ 40,000 bu = 1.4¢

Variable cost per bushel

Direct labor:

18 days of drying time. Drying operation checked twice daily. Time requirement 15 minutes/bin x 8 bins = 2 hours/day x 18 days = 36 hours x wage rate per hour ($2.50) = $90 ÷ 40,000 bu = 0.2¢

Electricity:

4,680 kWh x 8 (duplicates) = 37,440 kWh x 2.5¢/kWh = $9,360 ÷ 40,000 bu = 2.3¢

Repairs and maintenance:

Estimated annual repairs ($15) x 8 (duplicates) = $120 ÷ 40,000 bu = 0.3¢

Insurance on corn:

At rate of $3.60/$1,000 value/6 months or 0.9¢/bu with corn valued at $2.50/bu

Interest on working capital:

Direct labor (0.2¢) + electricity (2.3¢) + repairs and maintenance (0.3¢) + insurance (0.9¢) = 3.7¢ x 8% = .296¢ ÷ 4 (borrowed for 3 months) = .07¢

Automatic batch grain dryer, 40,000 bu

Fixed cost per bushel

Dryer depreciation:

$$\frac{\text{Original cost (\$13,170) - 5\% salvage value (\$658)}}{\text{Life (8 years)}} = \$1{,}564 \div 40{,}000 \text{ bu} = 3.9\text{¢}$$

Equipment depreciation:

$$\frac{\text{Original cost (\$2,859) - 5\% salvage value (\$143)}}{\text{Life (15 years)}} = \$181 \div 40{,}000 \text{ bu} = 0.4\text{¢}$$

Electrical hookup:

$$\frac{\text{Original cost (\$400) - no salvage value}}{\text{Life (20 years)}} = \$20 \div 40{,}000 \text{ bu} = \text{less than } 0.1 \text{ cent}$$

Insurance on dryer and equipment:

Original cost of dryer (13,170) + original cost of equipment ($2,859) = $16,029 x $6/$1,000 = $96 ÷ 40,000 bu = 0.2¢

Interest on investment:

Original cost of dryer ($13,170) + original cost of equipment ($2,859) + original cost of electrical hookup ($400) = $16,429 ÷ 2 = average value ($8,214) + land value ($30) = $8,244 x interest charge (8%) = $660 ÷ 40,000 bu = 1.6¢

Taxes:

Original cost of dryer ($13,170) + original cost of equipment ($2,859) + original cost of electrical hookup ($400) = $16,429 x assessment (30%) = $4,929 x 65 mills = 320 ÷ 40,000 bu = 0.8¢

Variable cost per bushel

Direct labor:

Hours of dryer operation (222) x wage rate per hour ($2.50) x 1/3 hour (time per check) = $185 ÷ 40,000 bu = 0.5¢

Electricity:

222 kWh x 4.5¢/kWh = $57 ÷ 40,000 bu = 0.1¢

Fuel cost:

$$40{,}000 \times 56 \text{ lb/bu} = 2{,}240{,}000 \text{ lb (wet weight)} \times \frac{\text{100 minus the wet percentage (25.5\%)}}{\text{100 minus the dry percentage (15.5\%)}}$$

= dry weight (1,975,008) = 264,992 lb of H_2O removed Btu/lb of H_2O (1850) x lb of water removed (264,992) = 490,235,200) Btu ÷ 91,500 Btu/gal LPG = 5,358 gal x cost/gal ($.30) = $1,607 ÷ 40,000 bu = 4.0¢

Repairs and maintenance:

2% of original cost of dryer and equipment ($16,029) = $321 ÷ 40,000 bu = 0.8¢

Insurance on corn:

At rate of $3.60/$1,000 value/6 months or 0.9¢/bu with corn valued at $2.50/bu

Interest on working capital:

Direct labor (0.5¢) + electricity (0.1¢) + LPG (4.0¢) + repairs and maintenance (0.8¢) + insurance (0.9¢) = 6.3¢ x 8% = .504¢ ÷ 4 (borrowed for 3 months) = 0.1¢

Continuous flow grain dryer, 40,000 bu

Fixed cost per bushel

Dryer depreciation:

$$\frac{\text{Original cost (\$18,240) - 5\% salvage value (\$912)}}{\text{Life (8 years)}} = \text{\$2,166} \div \text{40,000 bu} = 5.4¢$$

Equipment depreciation:

$$\frac{\text{Original cost (\$2,859) - 5\% salvage value (\$143)}}{\text{Life (15 years)}} = \text{\$181} \div \text{40,000 bu} = 0.4¢$$

Electrical hookup:

$$\frac{\text{Original cost (\$400) - no salvage value}}{\text{Life (20 years)}} = \text{\$20} \div \text{40,000 bu = less than 0.1 cent}$$

Insurance on dryer and equipment:

Original cost of dryer ($18,240) + original cost of equipment ($2,859) = $21,099 x $6/$1,000 = $127 ÷ 40,000 bu = 0.3¢

Interest on investment:

Original cost of dryer ($18,240) + original cost of equipment ($2,859) + original cost of electrical hookup ($400) = $21,499 ÷ 2 = average value ($10,750) + land value ($30) = $10,780 x interest charge (8%) = $862 ÷ 40,000 bu = 2.2¢

Taxes:

Original cost of dryer ($18,240) + original cost of equipment ($2,859) + original cost of electrical hookup ($400) = $21,499 x assessment (30%) = $6,450 x 65 mills = $419 ÷ 40,000 bu = 1.0¢

Variable cost per bushel

Direct labor:

Hours of dryer operation (222) x wage rate per hour ($2.50) x 1/3 hr (time per check) = $185 ÷ 40,000 bu = 0.5¢

Electricity:

1,263 kWh x 4.5¢/kWh = $57 ÷ 40,000 bu = 0.1¢

Fuel cost:

40,000 bu x 56 lbs/bu = 2,240,000 lb (wet weight x $\frac{\text{100 minus the wet percentage (25.5\%)}}{\text{100 minus the dry percentage (15.5\%)}}$ = dry weight (1,975,008) = 264,992 lb of H_2O removed. Btu/lb of H_2O removed (220) x lb of water removed (264,992) = 582,982,400 Btu ÷ 91,500 Btu/gal LPG = 6,317 gal x cost/gal ($.30) = $1,911 ÷ 40,000 bu = 4.8¢

Repairs and maintenance:

2% of original cost of dryer and equipment ($21,099) = $422 ÷ 40,000 bu = 1.1¢

Insurance on corn:

At rate of $3.60/$1,000 value/6 months or 0.9¢/bushel with corn valued at $2.50/bu

Interest on working capital:

Direct labor (0.5¢) + electricity (0.1¢) + LPG (4.5¢) + repairs and maintenance (1.1¢) + insurance (0.9¢) = 6.9¢ x 8% = .552¢ ÷ 4 (borrowed for 3 months) = 0.1¢

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