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AGRICULTURAL PROGRAMS IN SOLAR ENERGY

Landy B. Altman[1]

The U.S. agricultural system was developed with abundant supplies of low-cost energy which accounted for only a small fraction of the cost of supplying food, fiber, and wood products. Demands for energy are rapidly outstripping supply, and we can expect energy costs and availability to be significant factors in the future.

About 20 percent of the total energy used in the United States is related to the production, processing, marketing, distribution, and utilization of food, natural fiber, and forest products. As population increases both here at home and abroad, the demand for these products will increase and hence increase the demand for energy.

A comprehensive and balanced agricultural energy research, development, and demonstration program is essential to assure the efficient use of the 20 percent of the Nation's energy consumption used in the food system. Such a program would include the development and adoption of new energy-efficient technologies; the substitution of noncritical fuels and energy sources for oil and gas; and the protection of the environment from the effects of energy development and use.

The Congress established the Energy Research and Development Administration, ERDA, to the be lead Federal agency responsible for energy research, development, and demonstration. Before ERDA was formed in January 1975, the National Science Foundation had lead responsibility for solar energy research. Representatives of NSF arranged for the Department of Agriculture and the Agricultural Research Service to manage research on agricultural applications of solar energy with funds passed through to ARS from NSF. Responsibility for this research was passed from NSF to ERDA when ERDA was established.

The solar energy program was subdivided into five research areas, and a tentative allocation of funds was made to each area. Principal investigators for each area were selected, proposals were solicited, and peer panels selected the best proposals for funding. Table 1 shows the five research areas and the number of projects funded in each area.

[1] Energy Research Coordinator, USDA, ARS, Beltsville, Maryland

Table 1 Research on Agricultural Applications of Solar Energy

Research Area	Number of Projects
Solar Grain Drying	15
Applications of Solar Energy for the Drying of Peanuts, Forages, and Tobacco	6
Use of Solar Energy in Livestock Production	12
Solar Heating and Cooling of Greenhouses and Rural Residences	11
Solar Energy in Food Processing	6
Total	50

Of the above projects, 33 are at SAES, 11 in ARS laboratories, 3 in university laboratories, and 3 in industry laboratories.

Wind energy is considered solar in origin. ERDA has passed through to ARS funds to support research on wind energy for farm and remote installations. Research is underway on wind energy for space heating, irrigation pumping, refrigeration, and agricultural processing.

Research on the use of agricultural and forest residues for the production of energy is also a part of the solar energy program. ERDA has provided funds for an ARS study of the generation of methane in a digestor used in the processing of manure for refeeding to cattle. They are also funding other studies on the use of agricultural and forest wastes in the production of energy and chemicals.

A film on agricultural uses of solar energy is in the process of production by the USDA Film Production Unit. It gives a quick overview of the research on agricultural applications of solar energy and should set the stage for the solar grain drying conference.

OVERVIEW OF SOLAR GRAIN DRYING RESEARCH - FIELD TESTS

George H. Foster[1]

Direct application of solar energy has long been practiced for drying crops in the field, in the stack or windrow, on drying floors, and in ventilated sheds or cribs. However, the technical and economic feasibility of collecting and utilizing solar energy as a heat source in a drying system that would be compatible with present day crop production, harvesting, handling and storage systems has not been adequately established.

Funding of research for solar grain drying was initiated by the National Science Foundation in late 1974 in response to the 1973 fuel crisis and as a part of the U.S. effort toward energy self-sufficiency. Program sponsorship was assumed by the U.S. Energy Research and Development Administration (ERDA) in January 1975. The Agricultural Research Service ARS has been managing the research program with the help of the Cooperative State Research Service. Both are agencies of the U.S. Department of Agriculture.

THE RESEARCH PROGRAM

Proof of concept tests were started late in 1974 at seven State agricultural experiment stations and two ARS locations. In May 1975, solar rice drying work was added, along with a program of computer simulation research that will be discussed in a separate presentation.

Funding level, type of tests and participants were as follows:

1974-75 Phase I - Proof of Concept Tests
- Funded September 1974 - $150,000
  - 7 State agricultural experiment stations
  - 2 ARS locations

Phase II - Simulation Studies, Plus Rice Drying
- Funded May 1975 - $150,000
  - 4 State agricultural experiment stations (3 same as in Phase I)
  - 2 ARS locations (1 same as in Phase I)

[1]Agricultural Engineer and Research Leader, U.S. Grain Marketing Research Center, ARS-USDA, Manhattan, Kansas and Principal Investigator, Solar Grain Drying Program.

1975-76 Proof of Concept Tests, Plus Simulation
Funded September 1975 - $300,000
8 State agricultural experiment stations
(5 in 1975 program)
1 consulting firm
4 ARS locations (3 same as in 1975 program)

Currently, solar grain drying research is being conducted at 15 locations, consisting of 11 State agricultural experiment stations and 4 ARS locations, at a funding level of $530,000, as follows:

Solar Grain Drying Program--1976-77
Date funded - July 19, 1976
Number of projects funded - 15

Project Locations

State Agricultural Experiment Stations

Colorado	Kansas
Florida	Kentucky
Illinois	Missouri
Indiana	Nebraska
Iowa	Ohio
South Dakota	

Agricultural Research Service (USDA) Locations
W. Lafayette, Indiana
Ames, Iowa
Manhattan, Kansas
Beaumont, Texas

The initial approach to solar grain drying was to collect and utilize solar energy as a supplemental heat source for low-temperature drying of grain in storage. Solar energy was used alone or in combination with electric heat. Results of drying tests in which only solar energy was used were compared with results of natural air drying or drying with electric heat.

The current solar grain drying research program consists of:
(1) Field drying tests that have a demonstrational as well as a research objective.
(2) Evaluation of grain stirring devices as an aid to in-storage solar drying.
(3) Design, development, and testing of low-cost solar collectors suitable for grain drying.
(4) Development and testing of systems for storage of solar energy.
(5) Development and feasibility studies of alternate uses for solar collection systems that are used for grain drying.
(6) Development and testing of concentrating type solar collectors and their evaluation for high-temperature drying.

(7) Economic analysis of current solar-drying concepts.
(8) Mathematical modeling of solar collectors and solar drying systems.

Each of the eight research program segments is treated separately in this conference program, except for the evaluation of solar drying through field testing and demonstration. Therefore, I will confine my remarks to a brief report on the field drying studies.

FIELD TESTS--RESULTS AND PROGRESS

Eighteen solar-assisted drying tests were conducted with the 1974 crop at eight locations in the North Central region of the United States. One test was with soybeans, two were with grain sorghum, and 15 were with shelled corn. The tests were typical of low-temperature, in-storage drying, although in one test conditions were similar to those of batch-in-bin drying. Tests were continued at six locations in 1975 and eight locations in 1976.

All of the grain in the solar drying tests was successfully dried to safe storage moisture levels without significant spoilage. However, in some tests supplemental electric heat was used in addition to solar energy. Drying rates with solar systems were adequate for preventing spoilage and were in the range of those used for typical low-temperature drying--faster than with natural air drying and usually a little slower than with typical low-temperature heat drying systems.

Final grain moisture levels were lower in solar tests than in natural-air tests and generally higher than in tests with continuous heat added. In 1974 at the U.S. Grain Marketing Research Center (USGMRC) in Manhattan, Kansas, solar-dried corn averaged 13.2 percent moisture, and corn dried with natural air averaged 14.4 percent moisture after 20 days of drying at 2.5 and 2.8 cfm/bu (2.7 and 3.0 m^3/min-tonne). Similar results were obtained in sorghum drying tests in 1975 (Fig. 1). The average moisture content of the sorghum reached 15 percent in 2-4 days less time in solar tests than in natural air drying tests. More important, the maximum grain moisture content at the end of the solar test was nearly 14.5 percent when the moisture content of the top layer of sorghum in the natural air test was above 17 percent. An inflated plastic tube-type solar collector with an area of about 300 ft^2 (28 m^2) was used.

Efficiency at which the sensible heat in the drying air was used to remove moisture from grain was calculated for the tests conducted at the USGMRC. The utilization efficiency[1] of the sensible heat, natural plus solar, was equal to or a little higher than that in the natural air tests without solar heat. However, the heat utilization efficiency among different tests varied from 14 to 46 percent, a wide range and somewhat

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

lower than anticipated. About 20 percent of the total heat available for drying was from solar collectors. The other 80 percent was sensible heat in the air plus heat from energy supplied by the fan motor.

Minor grain quality deterioration was indicated by mold growth in some tests conducted at the USGMRC. Deterioration was generally confined to the surface grain that was last to dry. In one test with corn, *Penicillium* growth was slightly greater in the solar dried grain than in that dried with natural air. The percentage of kernels invaded by *Penicillium* increased from 10 percent initially to 60-80 percent after 2 weeks in the upper third of the grain near the center of the bin. *Aspergillus ochraceus* appeared in moderate amounts and *Alternaria* increased but did not reach levels considered important to the storage capability of the grain. There was no measurable mold activity in drying tests with sorghum and no measurable dry matter loss in any tests.

In Indiana in 1975, with an airflow rate of 2 cfm/bu (2.2 m^3/min-tonne), corn initially at 24 percent averaged 16 percent moisture content after 24 days in the solar bin. With a 10°F (5.6°C) temperature rise added continuously by an electric heater in a companion test, the corn averaged 14.6 percent moisture after 16 days.

In the Indiana test, the amount of solar energy collected by two 1,000 ft^2 (93 m^2) units replaced electric energy costing about 5 cents per bushel ($1.90/tonne) in low-temperature, electric drying. The solar collector investment represented about $1.50 per bushel ($57/tonne).

In Iowa, a 250 ft^2 (23.2 m^2) flat-plate collector supplied 18 percent of the drying energy, and the cost of drying 3,440 bu (90.5 tonnes) of corn with the energy so supplied was 2 cents per bushel ($0.76/tonne) less than that for low-temperature drying with electric heat. In South Dakota tests, 26 percent less electrical energy was used in the solar bin than in the check bin in 1974, and 55 percent less was used in 1975. Corn was dried from about 20 percent to about 14 percent moisture.

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

The cost effectiveness of solar energy at 1974-76 energy prices and availability has not been outstanding. As energy costs go up and collector designs are refined to reduce costs per unit of heat collected, the cost of solar energy relative to that of other fuels will improve. Naturally, solar collectors are more expensive in their developmental stage, and LP gas and electrical energy costs are relatively low in the Midwest.

The use of solar energy as a source of supplemental heat for in-storage grain drying shows promise of early adoption in the more humid areas of the United States. Supplemental heat is needed to lower the humidity of ambient air in order that drying can proceed to moisture levels safe for storage. As fuel increases in price or becomes unavailable for grain drying, solar energy should provide a viable alternative source of heat.

OTHER REPORTS ON SOLAR GRAIN DRYING

Agriculture Information Bulletin No. 401, entitled "Solar Grain Drying - Progress and Potential," was published in 1976 by the Agricultural Research Service, U.S. Department of Agriculture, and is available in single copies from the Office of Communication, U.S. Department of Agriculture, Washington, D.C. 20250. This publication and several other technical papers and reports that are based on recent research in solar grain drying are included in the references.

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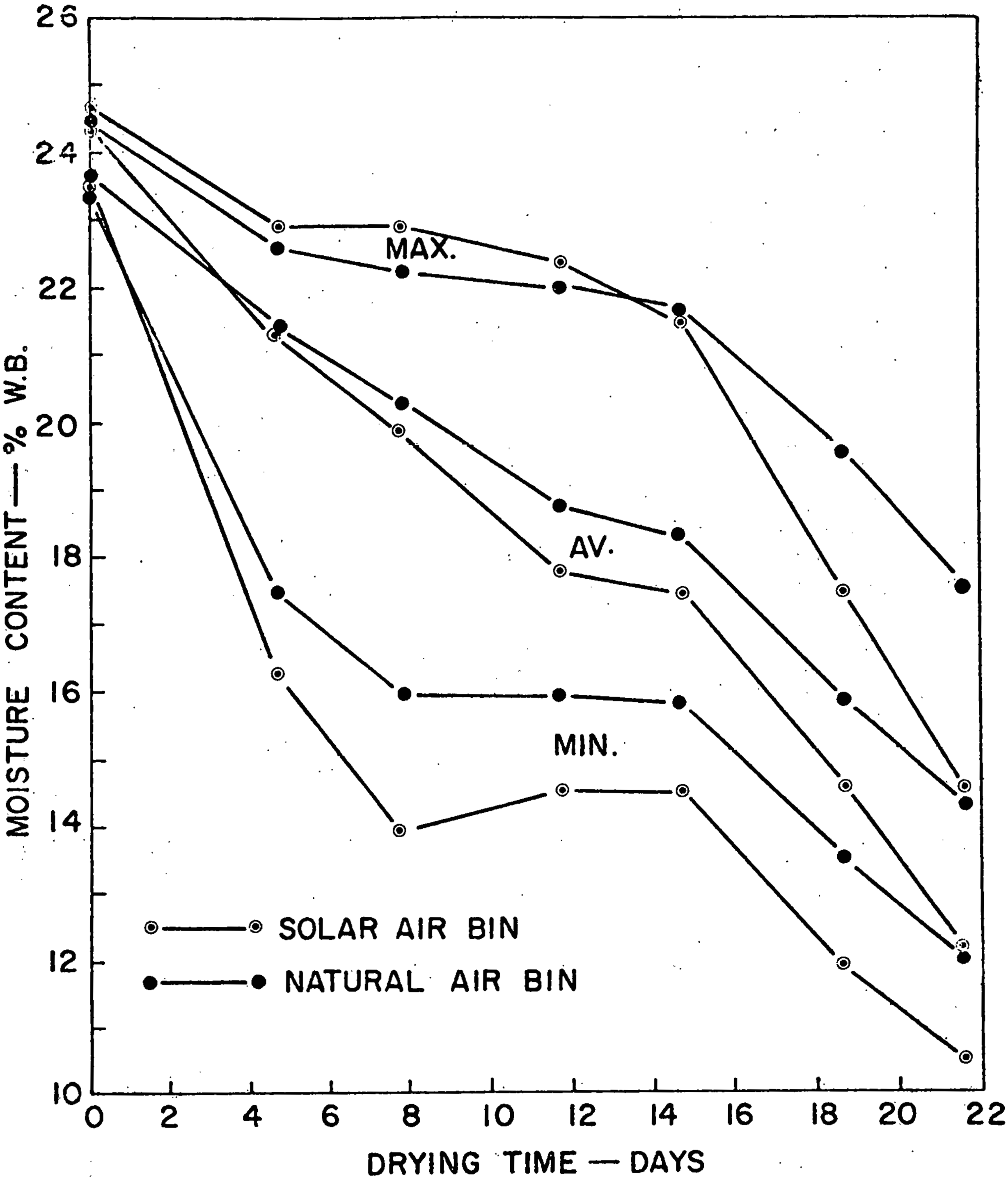

Figure 1. Typical moisture reduction patterns in sorghum dried with natural and solar-heated air.

SIMULATION OF SOLAR CORN DRYING IN THE MIDWEST

By Robert M. Peart[1]

INTRODUCTION

This paper reports the result of a one-year project by five groups working in this area. They are led by George H. Foster, U.S. Grain Marketing Research Center, USDA, ARS, Manhattan, Kansas; Dr. T.L. Thompson, Dept. of Agricultural Engineering, University of Nebraska, Lincoln, Nebraska; Dr. R. Vance Morey, Department of Agricultural Engineering, University of Minnesota, St. Paul, Minnesota; Dr. Harold M. Keener, Dept. of Agricultural Engineering, Ohio Agricultural Research and Developement Center, Wooster, Ohio, and myself at Purdue University. More details are available in the final reports of each of these projects available from the leaders when the reports are reviewed and cleared by ERDA.

BACKGROUND ON SIMULATION OF CORN DRYING

Early in the current work on solar grain drying, we felt that it would be worthwhile to utilize simulations to evaluate the feasibility of solar grain drying in comparison with current methods and to get some idea of the most feasible designs for solar grain drying systems in the midwest. The advantages of simulation are several. The primary advantage is that with adequate weather data and a reasonably valid model, many years of "experience" can be obtained in a relative short time. In addition, many different drying designs can be tested in this same short time and at much lower cost than setting up individual tests which can only be run in full scale during the corn harvest season once each year.

Many factors cause drying results for a solar system to vary from one year to the next. The first variable during the season is the planting date and variety, both under some control by the farmer, and next is the corn growing season itself which can determine whether the crop matures early or late. Once the crop is mature, the weather during the field dry-down period which brings the kernal moisture content from a range of 35 to 30% at maturity down to the desired 24 to 26% at harvest time can vary greatly, thus affecting harvest date. Lastly then the temperature and relative humidity of the ambient air during the drying period are very important to the drying process, and of course the incoming solar radiation is very important to the results of solar drying.

In addition to these weather variables that can make the same variety planted on the same date dry much differently in one year than in another, the design of the drying system also can cause great variations in results. The majority of the current work in solar corn drying has

[1]Agricultural Engineering Department, Purdue University, W. Lafayette, Indiana 47907

been in the low temperature range and under deep-bed bin drying conditions. Within this general area, there are still wide variations in system design variables, mainly the air flow rate through the corn and that through the collector and the solar collector size relative to the amount of corn. Another design variable is the heat storage capability of the system, and this factor has not yet been explored with simulation. Some drying test results have suggested that heat storage increases the effectiveness of utilization of the solar energy that is collected during the day.

The major processes involved in the grain drying system have been modeled, so the development of solar corn drying simulation systems began with considerable valuable background material.

Mathematical models that simulate grain drying processes have been proposed by a number of investigators (1, 2, 3, 10, 11, 5). Models that represent high-temperature, high-speed drying are based on equations expressing the drying rate of a defined but usually thin layer of grain. In low temperature drying, the method considered best adapted to the application of solar energy to crop drying, drying equations are more difficult to use because of the fluctuating temperature and humidity of the drying air. Flood, Sabbah, et al. (5) developed a low temperature drying model based on thin-layer drying equations developed from laboratory tests by Sabbah (8) in the temperature range of 36-70 deg. F. They also developed a model of the data of Steele and Saul (9) to evaluate the safe storage life of the corn during slow-drying.

When low temperature air is moved through deep beds of grain at relatively low air velocities it can be assumed to approach temperature and moisture equilibrium with the grain. The equilibrium approach to modeling low temperature drying systems was first suggested by Bloome and Shove (3) and further developed by Thompson (10). Thompson also added a prediction of deterioration expressed as dry matter decomposition based on empirical data from Steele (9).

SIMULATION MODELS FOR SOLAR CORN DRYING

The simulations in these current studies use models that are basically of the equilibrium type, the thin layer drying equation, or a combination. Under higher air flow rates, and with greater differences between the grain moisture content and the equilibrium moisture content of the air, the air and the grain are less likely to reach equilibrium in the time step used in the simulation, and the drying equation model is more appropriate. At lower air flows, the assumption of constant air state through the layer is not met as well, the thin layer drying models are more likely to over-predict the amount of drying that will actually occur, and the equilibrium model is better. The thin layer model used in the Purdue work was modified by a check of the equilibrium conditions of the air exhausting from each layer, so it is essentially a combination method. Keener at Ohio tested four different models using various forms of the drying equation and with an equilibrium check in at least one. Morey at Minnesota modified Thompson's original model by adding a thin layer equation to check conditions when the equilibrium assumption over-predicted drying rate. He used Thompson's equilibrium model for the rewetting case, but used a different equilibrium relative humidity equation for wetting than for drying to account for hysteresis. Foster at Manhattan, Kansas, used Thompson's equilibrium model with and without providing for hysteresis and he also modified the Thompson model by using the equilibrium equations by Chung and Pfost (4), by correcting the psychrometric data for barometric pressure differences due to local altitude, and by accounting for shrinkage during drying for better comparison with actual samples probed at constant depth intervals.

CORN MATURITY

At Purdue, we included the effect of the growing season on the date of corn maturity, so a unique harvest date was calculated for each year and desired starting moisture content. The method used was the modified growing degree-day calculation of Newman and colleagues (6), which accumulates the amount by which the daily average temperature exceeds 10 C (50 F.). The method uses half the sum of the maximum and minimum temperature as the average, but modifies the minimum to not allow it to be below 10 C (50 F.) and the maximum may not be above 30C (86 F.). Maturity dates differing by 5 weeks between years were found. Constant field drying rates of 1/2% w.b. per day above 26% and 1/3% per day below 26% were used to determine harvest dates after maturity, and drying was started on that day.

VALIDATION OF MODELS

These drying models have been reasonably well-validated. When evaluating the results of the computer simulation compared with the data from an actual bin, several considerations must be borne in mind. The measured results are taken from an actual farm size bin of grain being dried and there is always some variation in the air flow in various parts of the bin and thus in the moisture content at the same level throughout the bin. Also, a probe is used to obtain a sample from various depths in the bin, and these samples cannot be considered to be obtained exactly at the measured level. Thus the measured data must be considered to have some experimental error related to the sampling procedure and normal variations within a farm size bin. An apparently large variation can be obtained between simulated and measured moisture content at a given level if the drying front is very near that level in the bin. If the simulation calculates movement of the drying front at a slightly faster or slower rate than the actual drying front moves, the moisture content at a given point below the actual drying front will be several percentage points different than the measured moisture content even though the overall profile from top to bottom of the bin of measured vs. simulated moisture content will be reasonably close. Morey at Minnesota compared simulations with actual measurements in two drying bins in the fall of 1975, one supplemented with solar heat and one ambient air drying bin. Figure 1 is a plot of the simulated moisture content vs. measured points, showing the simulation using a 24-hour time increment and a one-hour time increment. The ambient air bin showed similar agreement.

Keener at Ohio compared and validated four different drying models. These included 1) the original log model (Moisture Ratio = e^{-kt}), Hukill's original drying equation applied to a deep bed, 2) a modified Michigan State University model using three different sets of thin layer drying equations depending upon the temperature range, 3) the same model with a different drying or moisture transfer equation, and 4) a model using a drying equation with the assumption that the kernel is a "2-lump" object and the drying equation is the sum of the drying rates from each of the two lumps. A typical result is shown in Figure 2 for the drying simulation using the moisture transfer equation developed by Sabbah (7).

Foster at Kansas tested various modifications of the Thompson model against actual drying tests. Figure 3 shows the plot of simulated and measured moisture content at two time periods throughout a depth of 100 inches in one of the drying tests. The following conclusions from the Kansas report by Foster give a good summary of that work.

"1) It appears that with the air flow rate used - 2.5 to 4.5 cfm/bu - the equilibrium assumption used in the Thompson model overstates the drying rate and confines drying to a zone or level in the grain of much less thickness than occurs in actual practice. This in effect means that the model predicts more efficient drying than is observed in actual practice when drying nears completion and the amount of undried grain diminishes. Therefore, the model should be improved by using a moisture transfer model that would describe the drying rate at the temperature and humidity conditions prevailing during a given time interval."

"2) There are two major problems in comparing the drying predicted by a mathematical model with that observed experimentally. First, the model assumes uniform progress of the drying front through the cross section of the grain bulk, and secondly, the drying rate is very dependent on air flow rate, which is difficult to measure accurately. Because of segregation and accumulation of fine and broken material under the spout when bins are filled with grain for drying, air flow is not normally uniform over the cross-section of the grain. This not only makes measurement of air flow difficult in experimental installations, it causes difficulty in locating grain moisture measuring points that provide an average moisture representative of the cross-section of the grain bulk."

"3) The Thompson model appears to perform adequately for assessing the relative feasibility of bin drying of grain with solar energy in various locations in the United States."

At Purdue, simulation results were compared with measured results in a bin of about 2500 bu., 18-ft. in diameter, 12 ft. deep with an air flow of about 2 cfm per bu. Results for two different times during the drying period and at the end of the test are shown in Figures 4, 5 and 6. All of the simulations at the various locations showed results that converged closer to the measured results as the end of the drying time was reached.

An indication of the validity of the spoilage simulation used in all this work was obtained in Foster's work in Kansas. Mold counts of samples were run in Kansas and in Indiana, but drying results were so successful that significant mold increases were noted in only one test in Kansas. There the model predicted 0.5% dry matter loss after 32 days, and the mold counts in the corn being simulated showed a marked increase between 25 and 35 days in the drying test.

RESULTS AND PRELIMINARY RECOMMENDATIONS

Thompson at Nebraska did a large series of simulation runs covering locations throughout the North Central region and with an average of 10 years of weather data per location utilizing natural air drying, solar supplemented drying and constant low level electric heat drying. His results were stated in terms of the minimum air flow required to complete drying before spoilage occurred in the upper layers. Figure 7 shows results for natural air drying for the twelve locations. For any given location, the air flow indicated by the 1.0 probability level is the air flow rate required for the worst drying year, that is the highest air flow requirement. Differences in the effect of solar drying at various locations in the mid-west are shown by Figures 8 and Figure 9. Figure 8 shows that for Indiana (Indianapolis weather data) a relatively low level of solar heat added (5.5 degree C per 4183 J per cm^2 per day) (5 degrees F per 500 Langleys per day) would result in a greatly reduced air flow requirement, while in Nebraska, where drier air, and perhaps cooler air prevails during the drying season, the solar supplementation reduces the air flow requirements very little.

These results of Thompson's agree with the results of Morey in Minnesota, who found that the average 2 to 2.5 degrees F temperature rise per day obtained by solar heat could be replaced by an increased air flow rate of approximately 10%, utilizing natural air. The Minnesota results indicate an interesting cost ratio for determining the economic feasibility of solar heat drying compared with natural air drying of corn starting at 22% moisture in St. Cloud, Minn. A 40% efficient solar collector with a 10-year life and a cost per square foot of 12 times the cost per kilowatt hour for electrical energy will give equal drying results at an equal overall cost including the fixed cost of the collector. This assumes 10% interest charges and constant energy cost over the 10-year period.

The Purdue work estimating date of maturity showed the need to consider this variation in future studies. Simulations of full-season variety corn maturity dates for central Indiana for a May 12 planting date were run for the 24 years 1952-75. Drying simulations were not run for all these years due to lack of solar radiation data, but maturity dates varied from Sept. 15 to Oct. 27 as shown in Table 1.

Table 1. Maturity dates for full-season corn planted on May 12 in central Indiana, 1952-1975. (3 years not mature before frost.)

Week of Maturity:	9/15	9/22	9/29	10/6	10/13	10/20	10/27
No. of Years:	2	4	4	7	2	1	1

Table 2. SUNDRY Simulation results for 2 cfm/bu., .5 sq. ft. collector (50% eff.)/bu., starting moisture 26%, drying until wettest layer < 18%, planting full-season corn 5/17, central Indiana.

Year	Started Drying	Time Required	Energy Cost @ 3¢/kwh	Top Layer Dry Matter Loss, %
1973	10/25	9 da. 17 hr.	1.7¢/bu.	.11
1974	11/1	11 da. 22 hr.	2.2¢/bu.	.26
1975	10/22	8 da.	1.5¢/bu.	.19

Variation in drying results can be seen in Table 2, where 1973, 1974 and 1975 are compared using one solar drying design. A solar drying system that worked well in 1973 might have been marginal and risky in 1974, as a dry matter loss of 0.5% in the top layer is considered noticeable spoilage.

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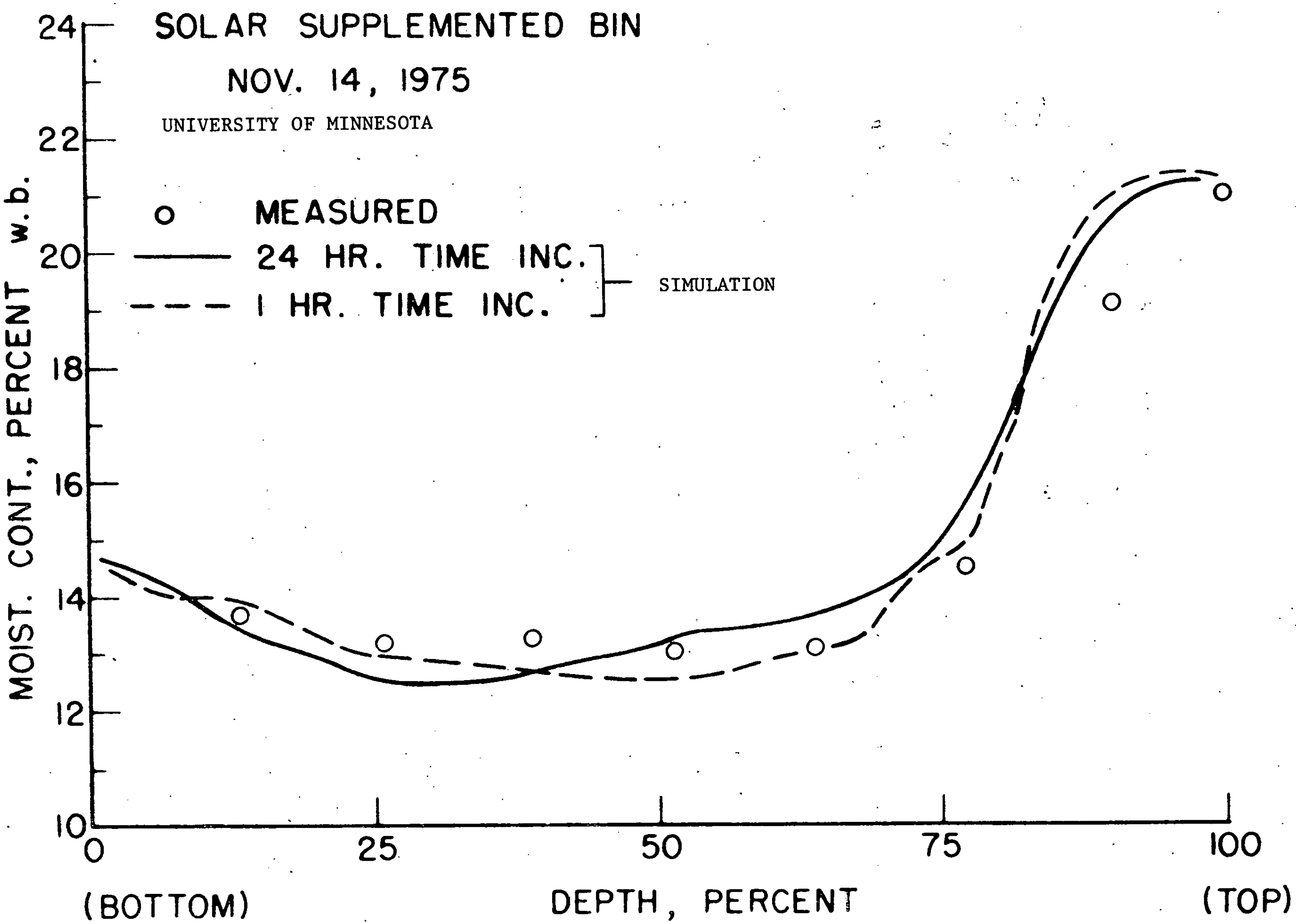


Figure 1. Moisture profile for the solar supplemented bin, measured and simulated.

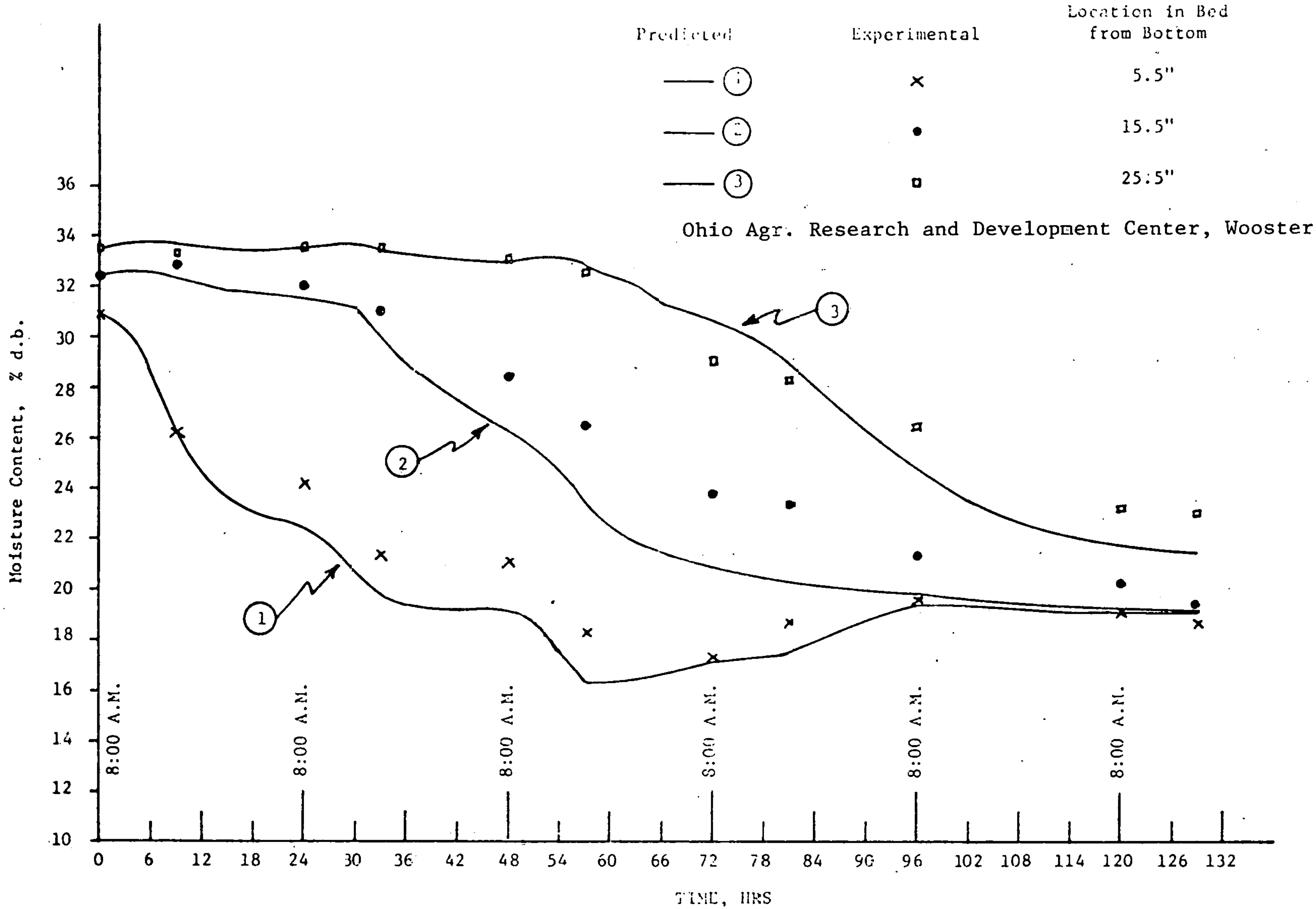


Figure 2. Simulated and measured corn moisture contents, Ohio.

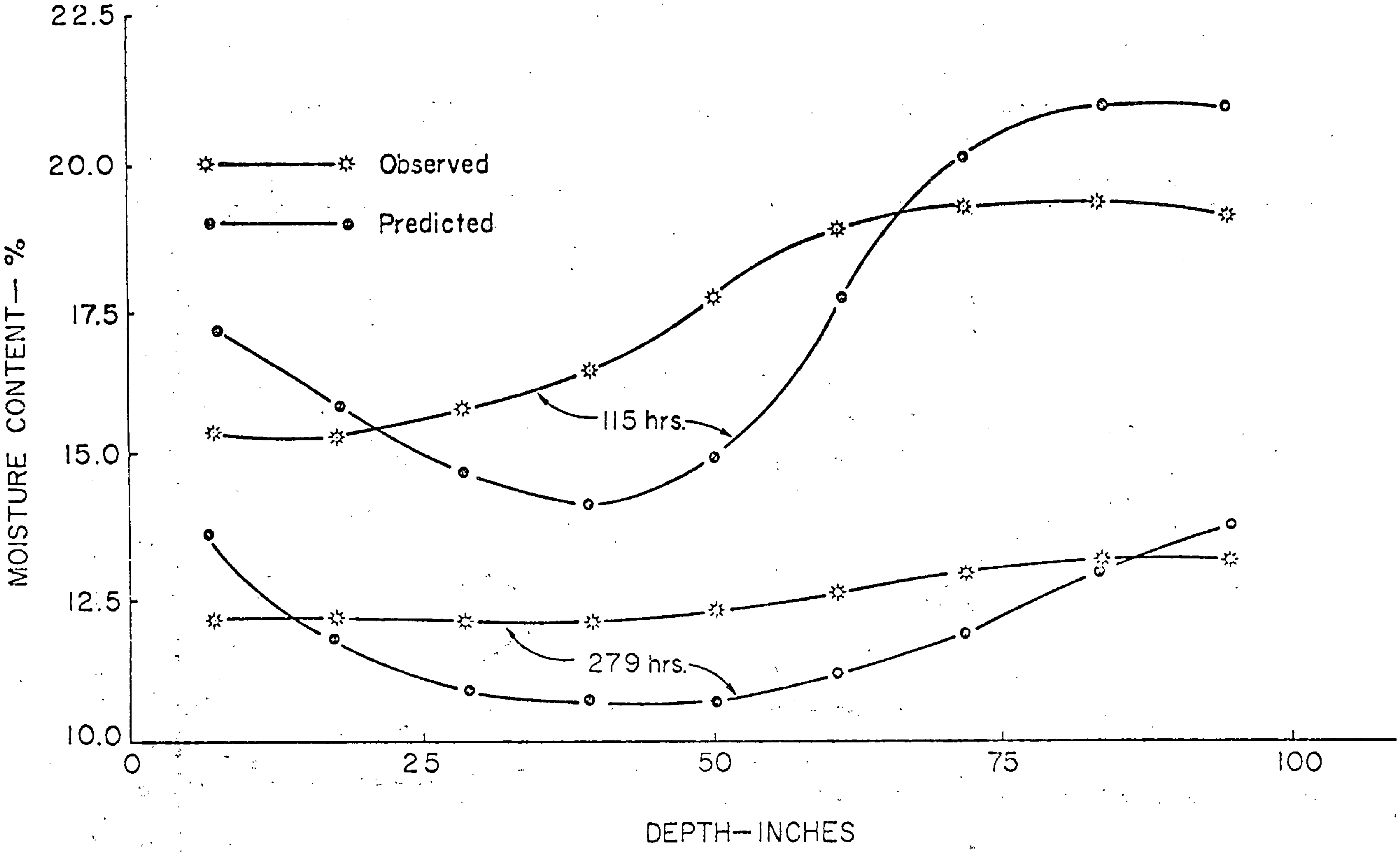
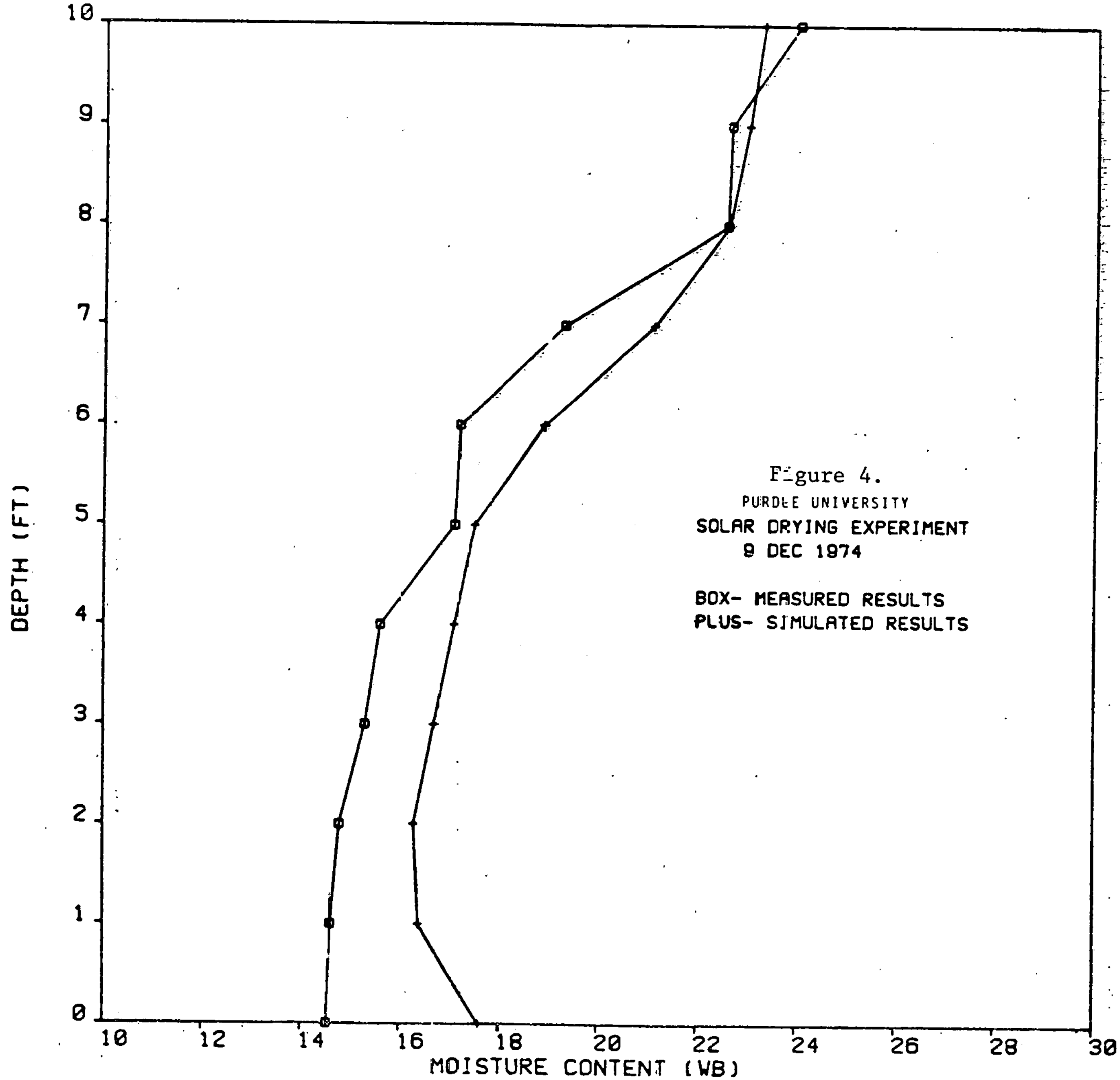


Figure 3. Simulated and observed corn moisture profiles, U.S. Grain Marketing Research Center, Manhattan, Kansas.


PURDUE UNIVERSITY
SOLAR DRYING EXPERIMENT
9 DEC 1974
BOX- MEASURED RESULTS
PLUS- SIMULATED RESULTS
DEPTH (FT)
MOISTURE CONTENT (WB)
0
1
2
3
4
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28
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Figure 4.

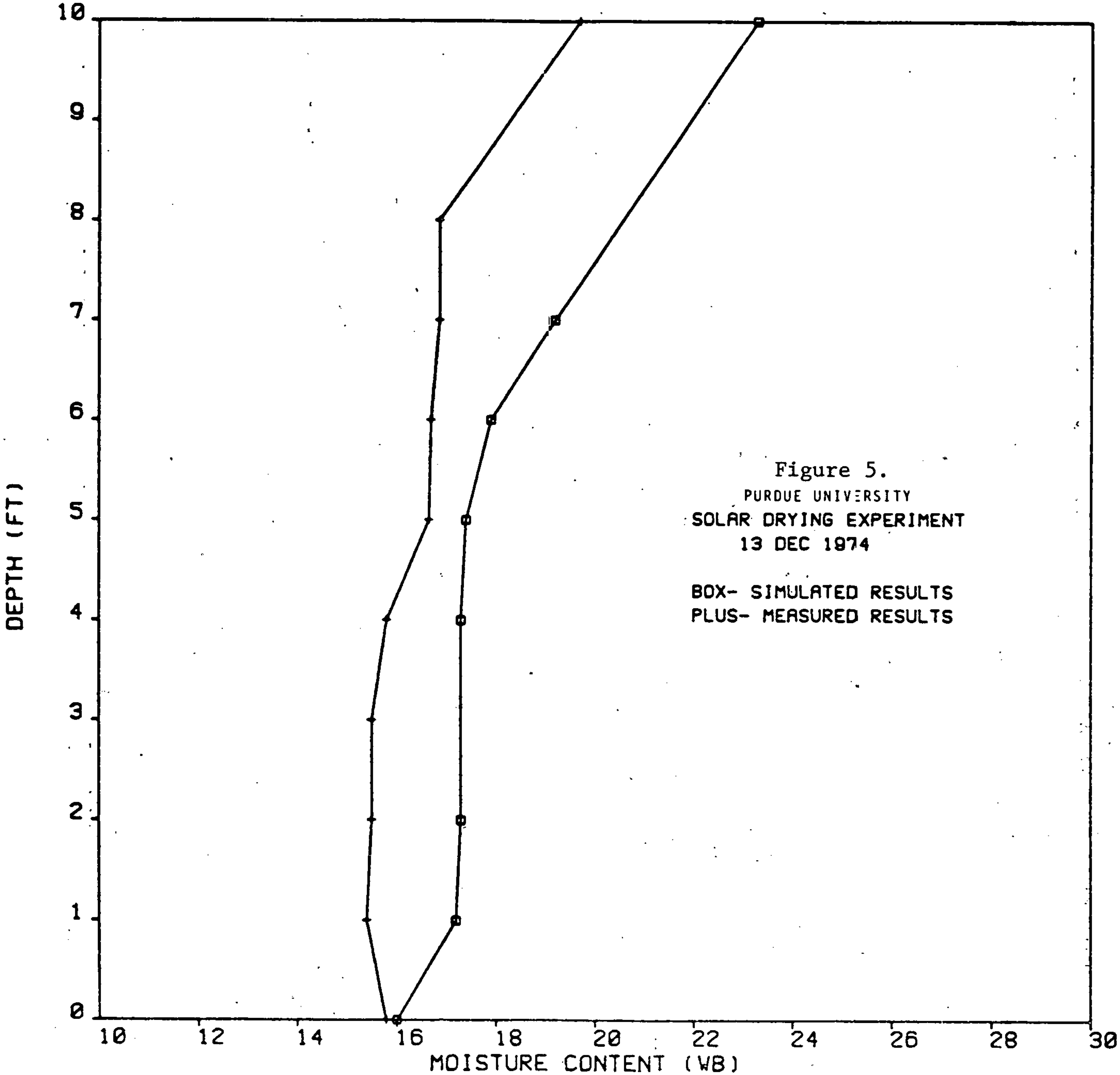
PURDUE UNIVERSITY
SOLAR DRYING EXPERIMENT
13 DEC 1974
BOX- SIMULATED RESULTS
PLUS- MEASURED RESULTS
DEPTH (FT)
MOISTURE CONTENT (WB)
0
1
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Figure 5.

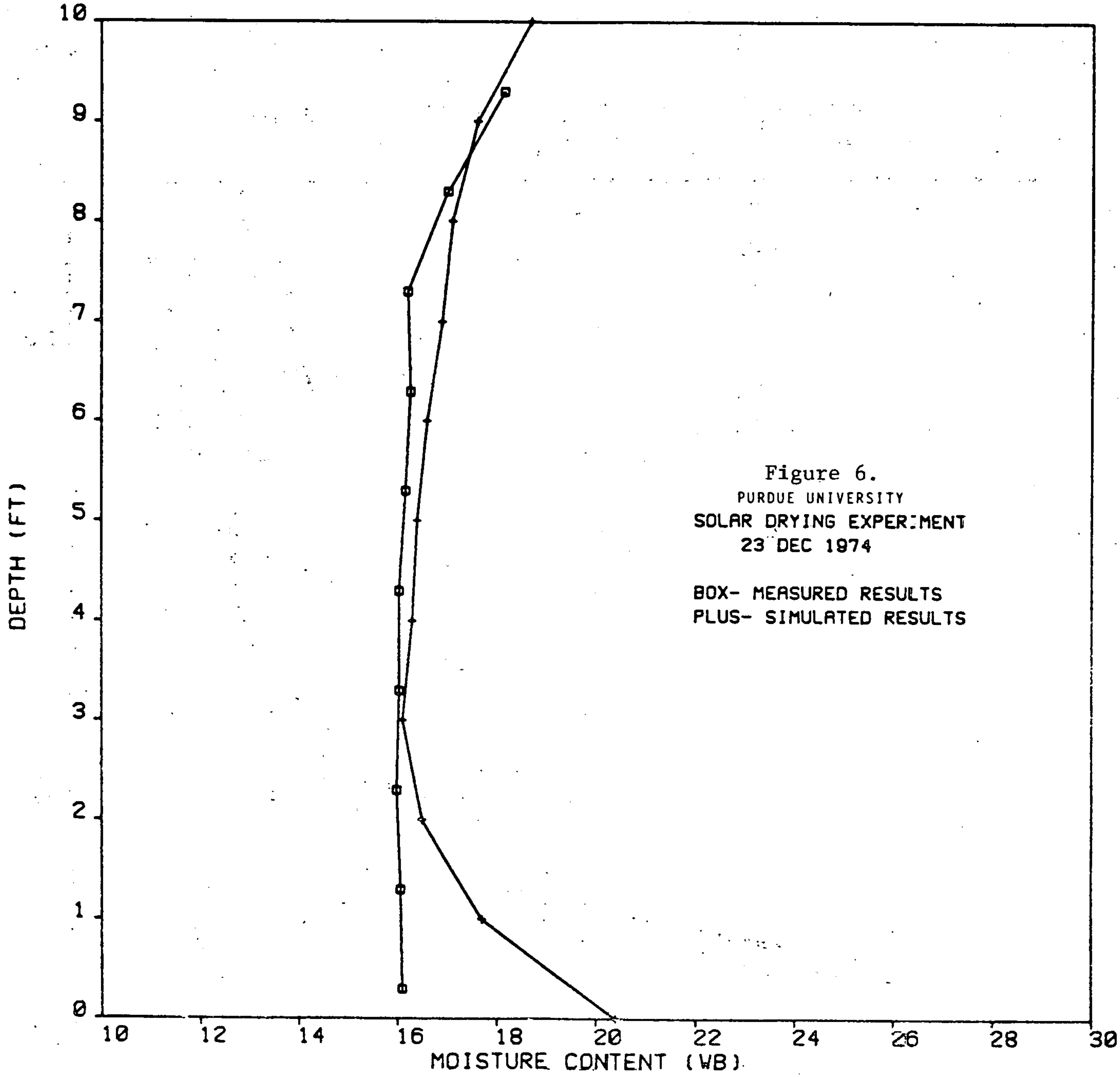
PURDUE UNIVERSITY
SOLAR DRYING EXPERIMENT
23 DEC 1974
BOX- MEASURED RESULTS
PLUS- SIMULATED RESULTS
DEPTH (FT)
MOISTURE CONTENT (WB)
0
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Figure 6.

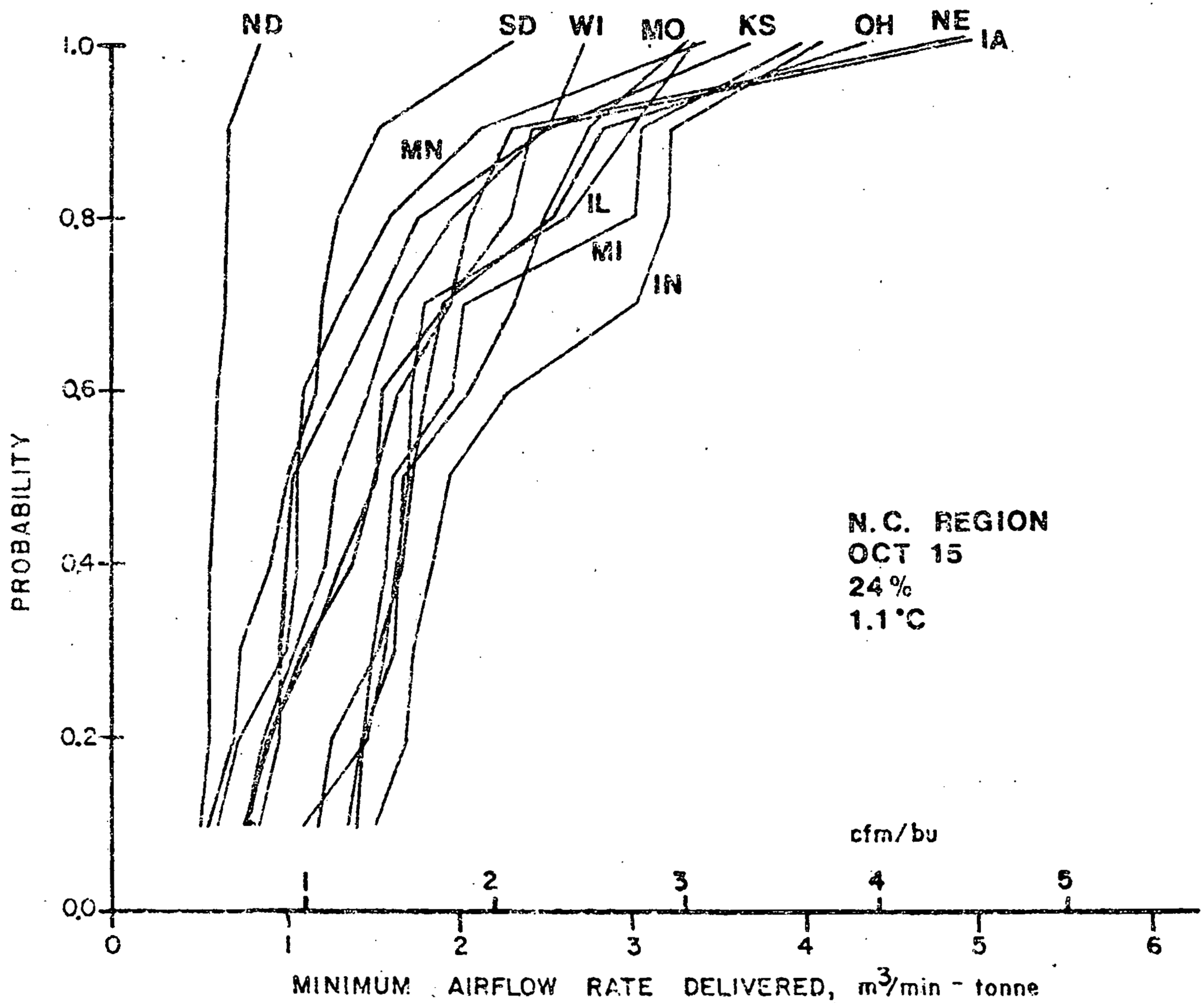

Figure 7. Predicted airflow requirements for the various locations across the North Central Region (1.1°C temperature rise from the fan motor, 24% corn and an October 15 harvest were assumed).

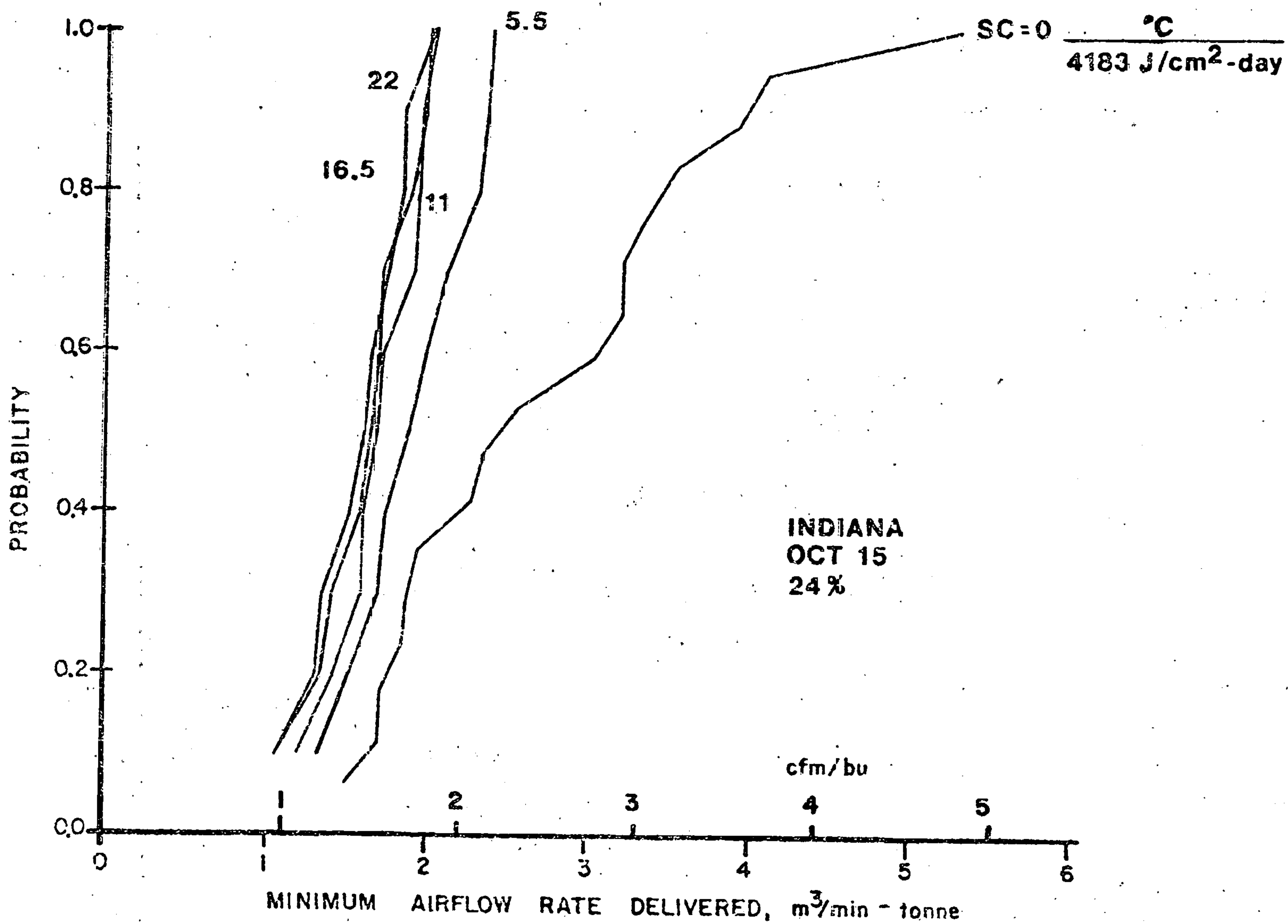

Figure 8. Effect of 5 levels of solar supplementation on the airflow required to dry 24% corn harvested October 15 at Indianapolis, Indiana.

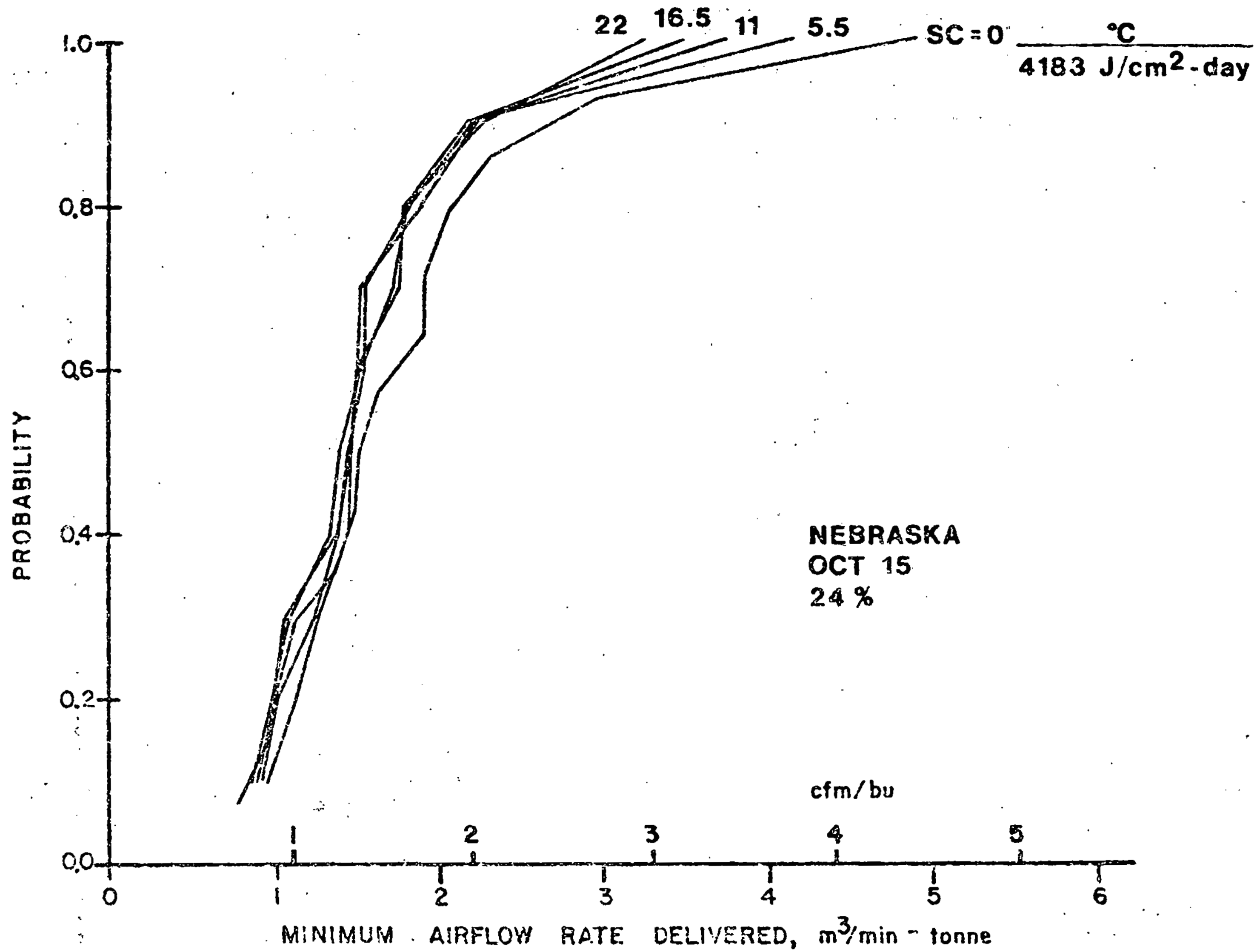

Figure 9. Effect of 5 levels of solar supplementation on the airflow required to dry 24% corn harvested October 15 at Lincoln, Nebraska.

SOLAR ENERGY AVAILABILITY

F. H. Buelow[1]

This paper is a review of the information that has been developed on the availability of solar energy, especially as it applies to grain drying systems. Most of the published information available on the subject is of a general nature. Solar energy applications reported are usually those which require energy over the entire winter or all year around. An attempt is made here to sort out appropriate information for grain drying applications, and then add procedures that may be the most helpful in the use of the information for research, design and planning activities.

The standard value of the solar constant (1353 W/m^2, 428 Btu/hr ft^2) may be considered as the basic parameter in developing information on availability of solar energy. However, it is of little practical value because of the variable attenuation of the earth's atmosphere, the changes in angle of incidence on any fixed flat plate collector, and the diffusions and reflections that may occur at a specific location and collector orientation. For these reasons most of the approaches to determination of solar energy availability are based on actual data that have been gathered by researchers for specific purposes, or by the various governmental meteorological agencies throughout the U. S. and the world.

MEASUREMENTS AND INSTRUMENTS

It seems appropriate to begin a discussion of solar energy availability by reviewing the most accurate means of determining energy levels at a given location -- that of direct measurement. For research and demonstrations involving solar collectors, direct, on-site, measurements are the only means of obtaining the necessary data with the accuracy required for drawing valid conclusions.

The usual procedure is to measure the total radiation impinging on a horizontal surface per unit time and area. The instrument used for this measurement is the pyranometer. It may be connected to integrators, recorders, or indicators to give the researcher the data in the form needed for processing. It should be noted that the data from the usual research installation cannot be expected to be better than $\pm 5\%$ accuracy. With frequent calibration, the accuracy may be increased to $\pm 2\%$.

For some situations the pyranometer may be placed at an incline to simulate the orientation of a collector and, thereby measure the energy falling on the collector. Under these circumstances it is important that the instrument and the collector both "see" the same direct, diffuse and reflected radiations. There is a possibility that the instrument calibration may vary with inclination and so should be used and calibrated as recommended by the manufacturer for these situations.

[1]Chairman, Agricultural Engineering Department,
University of Wisconsin-Madison

The actual measurement of solar energy at every location that a collector may be used is not practical, especially when designing solar grain drying systems for farm use. The designer needs to know how much solar energy will be available at certain times in the future at certain locations. Since atmospheric conditions are not highly predictable, even for a few days into the future, it is necessary to rely on climatalogical data from nearby weather stations and develop the probable solar energy availabilities from them. The determination of collector orientation and size are both dependent on this type of information.

ANGLES OF INCIDENCE

Equations giving the angle of incidence of direct solar radiation on a plane surface have been published in Benford and Bock (1), Buelow (2), and Duffie and Beckman (4). The general equation is:

$$\begin{aligned} \text{Cos}\,\theta = {} & \sin\delta\,\sin\phi\,\cos s \\ & - \sin\delta\,\cos\phi\,\sin s\,\cos\gamma \\ & + \cos\delta\,\cos\phi\,\cos s\,\cos\omega \\ & + \cos\delta\,\sin\phi\,\sin s\,\cos\gamma\,\cos\omega \\ & + \cos\delta\,\sin s\,\sin\gamma\,\sin\omega \end{aligned} \qquad (1)$$

where

ϕ = latitude (north positive)

δ = declination (i.e. the angular position of the sun at solar noon with respect to the plane of the equator) (north positive)

s = the angle between the horizontal and the plane (i.e. the slope)

γ = the surface azimuth angle, i.e. the deviation of the normal to the surface from the prime meridian, the zero point being due south, east positive and west negative

ω = hour angle, solar noon being zero, and each hour equalling 15° of longitude, with mornings negative and afternoons positive

θ = the angle of incidence of beam radiation, measured between the beam and the normal to the plane

The declination may be determined by the equation given by Cooper (3):

$$\delta = 23.45 \sin 0.9863\,(284 + n) \qquad (2)$$

where n is the day of the year and the angles are in degrees.

Equation (1) is simplified for south facing collectors, since the azimuth angle, γ, is zero, and, therefore, the equation becomes:

$$\begin{aligned}\cos\theta = {} & \sin\delta \sin\phi \cos s \\ & - \sin\delta \cos\phi \sin s \\ & + \cos\delta \cos\phi \cos s \cos\omega \\ & + \cos\delta \sin\phi \sin s \cos\omega \end{aligned} \tag{3}$$

For vertical surfaces, the slope, s, is 90° and so:

$$\begin{aligned}\cos\theta = {} & - \sin\delta \cos\phi \cos\gamma \\ & + \cos\delta \sin\phi \cos\gamma \cos\omega \\ & + \cos\delta \sin\gamma \sin\omega \end{aligned} \tag{4}$$

Note that at solar noon for a south facing collector

$$\theta = \delta - \phi + s \tag{5}$$

Although these equations could be used to determine the solar collector angle that would have the incoming radiation perpendicular to the plane of the collector at a given time and location, this procedure would not necessarily give the maximum total energy input for a given application.

One means of determining the optimum slope is to use equations given in Duffie and Beckman (4) which give the ratio of total radiation on a tilted surface to that on a horizontal surface. The equations may be programmed into a computer, and then combined with appropriate hourly weather data to give energy availability at various surface orientations. This method includes consideration of beam, diffuse and reflected radiation.

Another means of obtaining a value for optimum collector slope that does not require a computer is given by Buelow (2). By integrating equation (1) from sunrise to sunset an equation is obtained that gives a parameter, P, for evaluating the total daily direct solar energy falling on a fixed plane. Some values of P given by the equation for various latitudes, collector orientations, and times of the year are shown in tables in Appendix I of this paper. By finding the maximum value of P for a given latitude and time of year in the tables, the optimum collector slope will be indicated. For example, at a location of 40° latitude, the best angle for a south facing surface on October 16 ($\delta = -10$ from Eq. 2) is 55°.

SOLAR RADIATION DATA

One approach for predicting solar energy availability at a given location with a given collector orientation is to begin with climatalogical data available from the Environmental Data Service, National Climatic Center, National Oceanic and Atmospheric Administration, Asheville, N. C. 28801.

The data is available on punch cards and tape. This data from some 88 reporting stations in the U. S. gives solar energy falling on a horizontal surface each hour or each day, in some cases since 1952. Another source of radiation data is by Löf, Duffie and Smith (5) and gives average daily radiation on horizontal surfaces as monthly averages. Over 100 stations in the U. S. are listed. Some of their values are listed in Appendix II.

ESTIMATING SOLAR AVAILABILITY

The value for average daily radiation on a non-horizontal surface may be estimated by using the ratio of parameters for horizontal surfaces and non-horizontal surfaces given by Buelow (2) some of which appear in Appendix I of this paper:

$$\frac{\text{daily radiation on sloping surface}}{\text{daily radiation on horizontal surface}} = \frac{P_{\text{sloping surface}}}{P_{\text{horizontal surface}}} \quad (6)$$

For example, to estimate the average daily radiation on a surface with a 55° slope facing south near Indianapolis, Indiana, on October 16, one would find in Löf et al. (5) Appendix II, that the average daily radiation on the horizontal surface in October in Indianapolis is 293 cal/cm^2 day. The table in Appendix I for 40° latitude, on October 16 ($\delta = -10^{\circ}$) shows a parameter P for horizontal surfaces of 1.175 and for 55° south facing surfaces of 2.009. So the estimated daily solar radiation would be 293 x 2.009/1.175 = 501 cal/cm^2 day. This procedure for estimating solar energy availability assumes that the direct radiation is constant from sunrise to sunset, and that all incoming radiation is parallel to the sun's rays (no reflections or diffraction). Therefore, significant deviations from the estimates may occur, and drying system designs should be developed accordingly.

The parameters, P, given in Appendix I may also be used to determine total daily solar energy falling on an inclined surface if it is assumed that the solar radiation intensity is at a known constant value from sunrise to sunset. The equation for this estimate is

$$H = 13.72 \ P \ I \quad (7)$$

where H = direct solar energy falling on a surface, kJ/m^2 day

I = intensity of solar radiation on a surface perpendicular to the sun's rays, W/m^2

Equations (1), (3), (4) and (5) may be used to find the intensity of solar radiation on a surface at any given time by first solving one of these equations for cos θ and then using the equation

$$I_t = I \cos \theta \quad (8)$$

where I_t = intensity of solar radiation on a tilted surface, W/m^2

All methods of estimation have their shortcomings, but do give values that are valuable for the design and evaluation of solar grain drying systems. In general, the more detailed the actual data on solar energy is, the better will be the estimates. However, the time and computer costs will also be greater.

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Parameters, P, for south-facing surfaces

Latitude = 30°

δ \ s	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
23.5	2.265	2.226	2.174	2.108	2.029	1.938	1.834	1.719	1.594	1.459	1.317	1.167	1.012	.854	.694	.536	.381	.236	.107
20	2.201	2.182	2.149	2.102	2.041	1.967	1.879	1.780	1.668	1.546	1.414	1.274	1.126	.973	.817	.658	.500	.347	.203
15	2.100	2.108	2.102	2.081	2.046	1.996	1.932	1.854	1.763	1.660	1.546	1.421	1.287	1.144	.995	.840	.683	.524	.368
10	1.987	2.022	2.041	2.046	2.035	2.010	1.970	1.915	1.846	1.763	1.668	1.561	1.442	1.313	1.175	1.029	.876	.719	.559
5	1.865	1.923	1.967	1.996	2.010	2.009	1.992	1.961	1.915	1.854	1.780	1.692	1.591	1.478	1.354	1.221	1.078	.927	.771
0	1.732	1.813	1.879	1.932	1.970	1.992	2.000	1.992	1.970	1.932	1.879	1.813	1.732	1.638	1.532	1.414	1.286	1.147	1.000
-5	1.591	1.691	1.779	1.853	1.914	1.959	1.990	2.005	2.006	1.991	1.960	1.915	1.856	1.782	1.695	1.594	1.482	1.358	1.224
-10	1.442	1.560	1.667	1.761	1.841	1.907	1.959	1.996	2.018	2.025	2.016	1.991	1.952	1.898	1.829	1.746	1.650	1.542	1.421
-15	1.287	1.420	1.543	1.654	1.752	1.837	1.909	1.965	2.007	2.033	2.044	2.039	2.019	1.984	1.933	1.868	1.788	1.695	1.589
-20	1.126	1.272	1.409	1.534	1.648	1.749	1.837	1.911	1.971	2.015	2.045	2.058	2.056	2.038	2.005	1.957	1.893	1.815	1.724
-23.5	1.012	1.165	1.309	1.443	1.566	1.677	1.775	1.860	1.931	1.987	2.028	2.053	2.063	2.057	2.035	1.998	1.946	1.879	1.797

Latitude = 35°

δ \ s	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
23.5	2.291	2.265	2.226	2.174	2.108	2.029	1.938	1.834	1.719	1.594	1.459	1.317	1.167	1.012	.854	.694	.536	.381	.236
20	2.206	2.201	2.182	2.149	2.102	2.041	1.967	1.879	1.780	1.668	1.546	1.414	1.274	1.126	.973	.817	.658	.500	.347
15	2.077	2.100	2.108	2.102	2.081	2.046	1.996	1.932	1.854	1.763	1.660	1.546	1.421	1.287	1.144	.995	.840	.683	.524
10	1.939	1.987	2.022	2.041	2.046	2.035	2.010	1.970	1.915	1.846	1.763	1.668	1.561	1.442	1.313	1.175	1.029	.876	.719
5	1.792	1.865	1.923	1.967	1.996	2.010	2.009	1.992	1.961	1.915	1.854	1.780	1.692	1.591	1.478	1.354	1.221	1.078	.927
0	1.638	1.732	1.813	1.879	1.932	1.970	1.992	2.000	1.992	1.970	1.932	1.879	1.813	1.732	1.638	1.532	1.414	1.286	1.147
-5	1.478	1.591	1.691	1.779	1.853	1.913	1.958	1.989	2.004	2.004	1.989	1.959	1.914	1.854	1.780	1.693	1.592	1.480	1.356
-10	1.313	1.441	1.559	1.665	1.758	1.838	1.903	1.955	1.991	2.012	2.018	2.010	1.984	1.944	1.889	1.820	1.737	1.641	1.533
-15	1.144	1.286	1.417	1.538	1.648	1.744	1.828	1.898	1.953	1.993	2.018	2.028	2.022	2.001	1.965	1.913	1.848	1.768	1.674
-20	.973	1.125	1.267	1.401	1.523	1.634	1.732	1.817	1.889	1.946	1.988	2.015	2.027	2.023	2.004	1.970	1.920	1.856	1.778
-23.5	.854	1.010	1.158	1.298	1.427	1.546	1.653	1.747	1.828	1.895	1.948	1.986	2.009	2.016	2.008	1.985	1.947	1.894	1.826

Latitude = 40°

δ \ S	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
23.5	2.305	2.291	2.265	2.226	2.174	2.108	2.029	1.938	1.834	1.719	1.594	1.459	1.317	1.167	1.012	.854	.694	.536	.381
20	2.198	2.206	2.201	2.182	2.149	2.102	2.041	1.967	1.879	1.780	1.668	1.546	1.414	1.274	1.126	.973	.817	.658	.500
15	2.040	2.077	2.100	2.108	2.102	2.081	2.046	1.996	1.932	1.854	1.763	1.660	1.546	1.421	1.287	1.144	.995	.840	.683
10	1.876	1.939	1.987	2.022	2.041	2.046	2.035	2.010	1.970	1.915	1.846	1.763	1.668	1.561	1.442	1.313	1.175	1.029	.876
5	1.706	1.792	1.865	1.923	1.967	1.996	2.010	2.009	1.992	1.961	1.915	1.854	1.780	1.692	1.591	1.478	1.354	1.221	1.078
0	1.532	1.638	1.732	1.813	1.879	1.932	1.970	1.992	2.000	1.992	1.970	1.932	1.879	1.813	1.732	1.638	1.532	1.414	1.286
-5	1.354	1.478	1.590	1.691	1.778	1.852	1.912	1.957	1.987	2.002	2.002	1.987	1.956	1.911	1.851	1.777	1.690	1.590	1.477
-10	1.175	1.312	1.440	1.557	1.662	1.754	1.833	1.897	1.948	1.984	2.004	2.009	1.999	1.974	1.934	1.879	1.810	1.727	1.631
-15	.995	1.143	1.282	1.412	1.531	1.638	1.733	1.815	1.882	1.936	1.975	1.998	2.007	2.000	1.978	1.941	1.889	1.823	1.743
-20	.817	.971	1.119	1.258	1.387	1.505	1.613	1.708	1.790	1.858	1.912	1.951	1.997	1.986	1.981	1.960	1.925	1.875	1.811
-23.5	.694	.851	1.001	1.144	1.278	1.402	1.520	1.618	1.708	1.784	1.848	1.897	1.931	1.951	1.956	1.947	1.922	1.883	1.829

Latitude = 45°

δ \ S	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
23.5	2.307	2.305	2.291	2.265	2.226	2.174	2.108	2.029	1.938	1.834	1.719	1.594	1.459	1.317	1.167	1.012	.854	.694	.536
20	2.178	2.198	2.206	2.201	2.182	2.149	2.102	2.041	1.967	1.879	1.780	1.668	1.546	1.414	1.274	1.126	.973	.817	.658
15	1.990	2.040	2.077	2.100	2.108	2.102	2.081	2.046	1.996	1.932	1.854	1.763	1.660	1.546	1.421	1.287	1.144	.995	.840
10	1.800	1.876	1.939	1.987	2.022	2.041	2.046	2.035	2.010	1.970	1.915	1.846	1.763	1.668	1.561	1.442	1.313	1.175	1.029
5	1.608	1.706	1.792	1.865	1.923	1.967	1.996	2.010	2.009	1.992	1.961	1.915	1.854	1.780	1.692	1.591	1.478	1.354	1.221
0	1.414	1.532	1.638	1.732	1.813	1.879	1.932	1.970	1.992	2.000	1.992	1.970	1.932	1.879	1.813	1.732	1.638	1.532	1.414
-5	1.221	1.354	1.478	1.590	1.690	1.777	1.850	1.910	1.955	1.985	2.000	1.999	1.984	1.953	1.908	1.848	1.774	1.687	1.586
-10	1.029	1.174	1.311	1.437	1.553	1.656	1.747	1.825	1.889	1.939	1.974	1.993	1.998	1.987	1.962	1.921	1.866	1.796	1.713
-15	.840	.993	1.139	1.276	1.403	1.519	1.624	1.716	1.795	1.861	1.913	1.960	1.972	1.979	1.971	1.948	1.910	1.858	1.792
-20	.658	.814	.964	1.106	1.240	1.365	1.479	1.582	1.672	1.750	1.815	1.866	1.903	1.925	1.933	1.926	1.904	1.868	1.817
-23.5	.536	.691	.840	.983	1.119	1.246	1.364	1.471	1.567	1.652	1.723	1.782	1.827	1.858	1.875	1.877	1.866	1.840	1.800

Latitude = 50°

δ \ S	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
23.5	2.301	2.307	2.305	2.291	2.265	2.226	2.174	2.108	2.029	1.938	1.834	1.719	1.594	1.459	1.317	1.167	1.012	.854	.694
20	2.147	2.178	2.198	2.206	2.201	2.182	2.149	2.102	2.041	1.967	1.879	1.780	1.668	1.546	1.414	1.274	1.126	.973	.817
15	1.929	1.990	2.040	2.077	2.100	2.108	2.102	2.081	2.046	1.996	1.932	1.854	1.763	1.660	1.546	1.421	1.287	1.144	.995
10	1.712	1.800	1.876	1.939	1.987	2.022	2.041	2.046	2.035	2.010	1.970	1.915	1.846	1.763	1.668	1.561	1.442	1.313	1.175
5	1.497	1.608	1.706	1.792	1.865	1.923	1.967	1.996	2.010	2.009	1.992	1.961	1.915	1.854	1.780	1.692	1.591	1.478	1.354
0	1.286	1.414	1.532	1.638	1.732	1.813	1.879	1.932	1.970	1.992	2.000	1.992	1.970	1.932	1.879	1.813	1.732	1.638	1.532
-5	1.078	1.220	1.354	1.477	1.588	1.688	1.775	1.848	1.907	1.952	1.982	1 996	1.996	1.980	1.949	1.904	1.844	1.770	1.682
-10	.876	1.028	1.172	1.307	1.432	1.546	1.648	1.738	1.814	1.877	1.926	1.959	1.978	1.982	1.971	1.945	1.904	1.848	1.779
-15	.683	.839	.988	1.130	1.263	1.387	1.500	1.601	1.691	1.768	1.831	1.880	1.915	1.935	1.941	1.932	1.908	1.870	1.817
-20	.500	.655	.804	.947	1.083	1.210	1.329	1.437	1.534	1.620	1.693	1.754	1.801	1.834	1.854	1.859	1.850	1.827	1.791
-23.5	.381	.531	.676	.816	.949	1.076	1.194	1.303	1.403	1.491	1.569	1.634	1.687	1.727	1.754	1.768	1.768	1.754	1.728

APPENDIX II

Data from Löf, Duffie and Smith (5).

Location	Latitude	Sept.	Oct.	Nov.
		Average total radiation on a horizontal surface, calories/cm^2		
Ames, Ia.	42° 02'	367	274	187
Bismarck, N.D.	46° 46'	382	273	161
Cleveland, Ohio	41° 24'	376	263	141
Columbia, Mo.	38° 58'	448	324	222
Columbus, Ohio	40° 00'	422	286	178
Dodge City, Kansas	37° 46'	493	380	280
Indianapolis, Ind.	39° 44'	405	293	176
Lemont, Ill.	41° 42'	384	265	157
Lincoln, Neb.	40° 52'	412	325	207
Madison, Wis.	43° 08'	384	265	150
Manhattan, Kansas	39° 12'	392	293	215
North Omaha, Neb.	41° 22'	396	294	198
Put-in-Bay, Ohio	41° 39'	399	295	157
Rapid City, S.D.	44° 02'	430	314	205
St. Cloud, Minn.	45° 35'	360	241	146

SOLAR ENERGY COLLECTORS FOR DRYING GRAIN

Gene C. Shove[1]

COVERED PLATE COLLECTORS

Flat plate solar energy collectors utilizing air as the medium for transporting heat are ideally suited to grain drying since grain drying utilizes large volumes of air and large areas of flat surfaces are readily available on many farm buildings. Flat plate solar collectors are simple in design and construction since the flat plate collector consists primarily of a flat plate for absorbing the energy and a cover of flat clear material (Fig. 1). The clear cover material readily transmits radiation from the sun, however, it is essentially opaque to the longer wave length energy emitted from the absorber plate after it is received. When air is moved over the absorber plate through the space created by the clear cover, the temperature of the air is increased. This solar heated air can then be used in a process requiring heated air, for example, grain drying.

BARE PLATE COLLECTORS

Although covered plate collectors are more efficient than bare plate collectors, bare plate collectors may have an application in some grain drying situations. A bare plate collector is very similar to a covered plate collector except the cover is omitted (Fig. 2). When the cover is omitted, some means must be provided for moving air along the back side of the bare absorber plate. This is usually accomplished by using some material having an insulation value back of the plate to create an air space. Air moved along the back side of the plate is heated by convection. Energy emitted from the face of the bare plate is lost since it reradiates to the atmosphere. Wind blowing across the face of a bare plate collector also diminishes the energy collected as compared to a covered plate collector.

Although bare plate collectors are not very efficient, their construction requires a minimum of relatively inexpensive materials. A bare plate collector can be installed on the side of a grain bin by building a secondary wall around the bin and painting it black. This secondary wall becomes the black energy absorbing surface and when the air moved by the drying fan is pulled behind this wall some of the sun's energy will be transferred to the air.

COLLECTORS INCORPORATED INTO BUILDINGS

Perhaps a more logical use of a bare plate collector is the adaptation of the roof and/or wall of a building to serve as a flat bare plate solar energy collector. A chamber for moving air along the backside

[1]Professor of Agricultural Engineering, University of Illinois, Urbana, Illinois

of a wall or along the underside of a roof can be created by the installation of a material to create a space for directing air along these metal surfaces. For maximum efficiency the roof and/or wall should be of a dark color, preferably black.

Since covered plate solar collectors are more efficient than bare plate collectors, it may be more desirable to incorporate a covered plate collector into the roof and/or wall of a building. Clear corrugated fiberglass can be used as the external roof and wall materials, placed over a black absorbing surface (Fig. 3). Air is then moved through the space created by the clear fiberglass and the black energy absorbing surface. Incorporating a collector into the roof and/or wall of a building requires a minimal change in the building's design and construction since the collector becomes a part of the roof and/or wall.

Solar collectors can be placed on the side wall of grain drying bins by painting the bin wall black, to act as the absorbing surface, and installing a secondary wall of clear fiberglass around the portion of the bin which the sun rays strike. Generally, more than one half of the circumference of a bin can serve as a solar collector; however, only a portion of the total collector surface area is effective at any given time. However, throughout the day the effective area remains essentially constant as the sun moves from east to west. Although such a collector is curved around the bin, it will function essentially as a flat plate collector.

Roof and wall collectors have essentially the same characteristics as any flat plate solar energy collector. They collect both the beam and diffuse radiation. They are mechanically simple, in this case actually becoming a part of the building, and consequently require little maintenance. Since a building roof or wall cannot be moved, the collector has the disadvantage of being mounted in a stationary position which prevents any tracking of the sun.

SUSPENDED PLATE COLLECTOR

Another configuration of a flat plate collector is the suspended plate collector (Fig. 4). Since air is moved along both sides of the suspended absorber plate, these collectors are more efficient than collectors in which the air is moved along only one side of the absorber plate. A suspended plate collector requires some additional material and is slightly more complicated; however, suspended plate collectors may have some application to grain drying. Walls and roofs of buildings could be constructed as suspended plate collectors without much difficulty. The collector chosen for a particular building will depend somewhat on the design of the building and the additional cost required to construct the wall or roof as a solar collector.

EFFICIENCY

The efficiency of a solar collector can be related to the temperature rise of the air passing through the collector. As the mass flow rate through a collector increases, the temperature rise through the collector decreases and temperature differentials tend to be minimized. Minimizing the temperature differential between the absorber plate and the air decreases losses, with a corresponding increase in the useful energy gain. The mass flow rate in collectors applied to grain drying can be higher than in many other applications because of the large volume of air used in grain drying. If excessive frictional losses can be avoided, all the air moved by the drying fan can be pulled through the collector. In some installations this will not be possible because frictional losses will become excessive and cause a significant decrease in the amount of air supplied to the drying bin. In such situations, it will be necessary to valve only a portion of the fan air delivery through the collector. Even so, large volumes of air will be involved and high flow rates can be maintained in the collector.

Some measure of the performance of a solar collector must be made to determine whether or not it is cost effective. One measure of performance is to compute a collector efficiency as the ratio of the useful energy gain to the incident solar energy. Such a computation can be made for solar grain drying applications by determining the airflow and the temperature rise of the air. This information allows the determination of the useful gain, that is, the energy imparted to the air. A pyranometer can be used at the site to measure the incident solar energy.

SUMMARY

There are numerous configurations of solar energy collectors, for example, collectors can be designed to concentrate energy to obtain very high temperatures. High temperatures are appropriate for some drying methods; however, it appears that solar energy will be first applied to drying methods not requiring high temperature rises. The requirement of a small temperature rise over an extended period of time is very suitable to the application of solar energy. Therefore it appears low temperature solar drying may become an accepted practice.

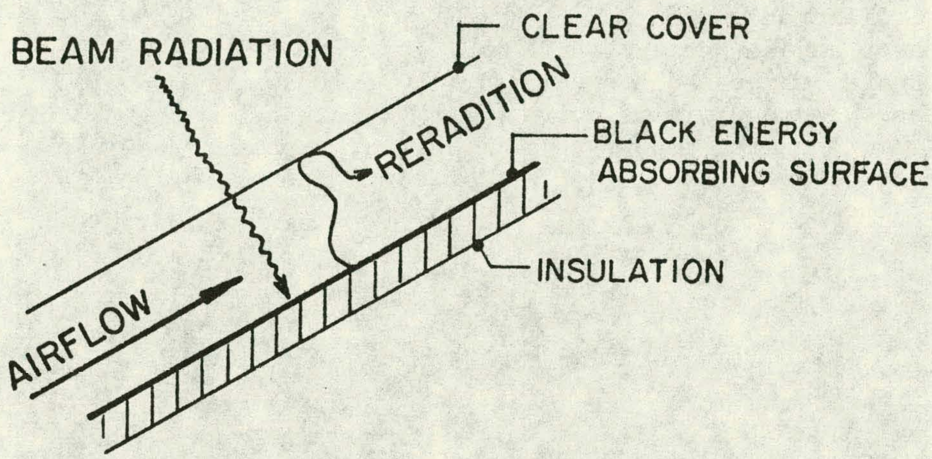

Fig. 1. Covered plate solar energy collector.

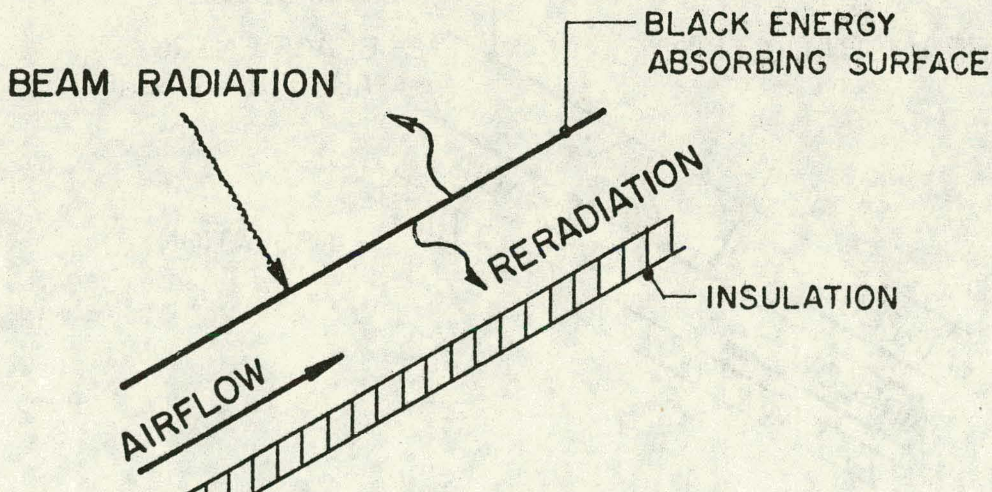

Fig. 2. Bare plate solar energy collector.

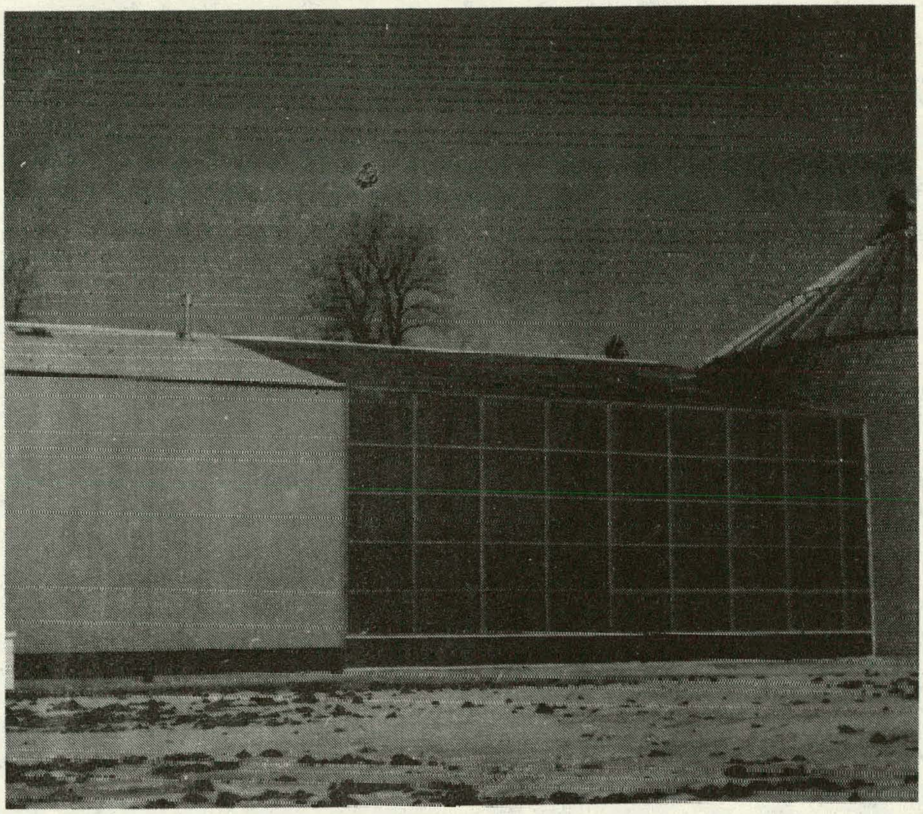

Fig. 3. Covered plate solar collector incorporated into the roof and wall of a farm building.

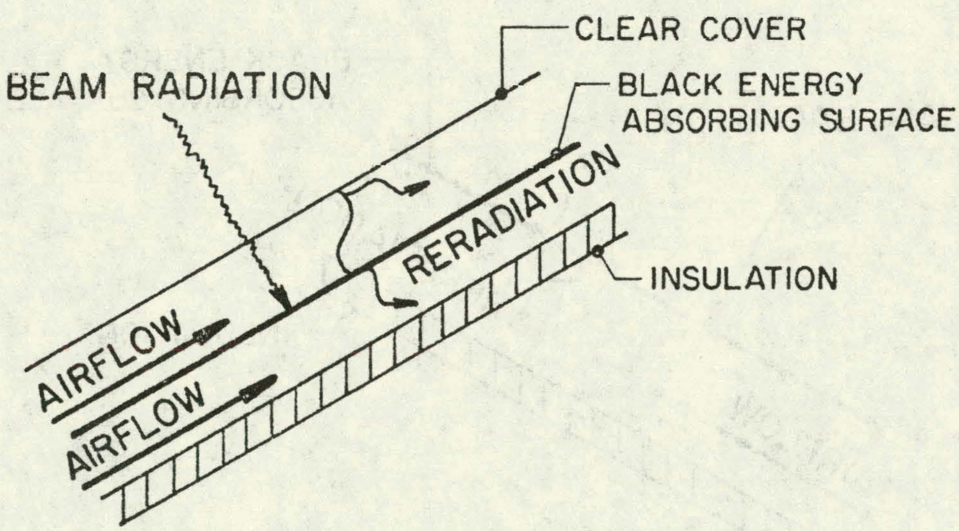

Fig. 4. Suspended plate solar energy collector.

SOLAR COLLECTOR ORIENTATION

William H. Peterson[1]

In designing solar collectors, it is important to know what surface orientations will receive the most solar energy. Since certain surface orientations appear repeatedly in standard building practices, it is of interest to know the amounts of solar energy received on those surfaces. Although the position of the sun changes hourly, daily, and seasonally, its movements are repeated annually, and from available charts and tables (1) it is possible to predict the amount of solar radiation received on a surface in a given time, on a clear day.

BASIC CONSIDERATIONS

Figure 1 shows the pattern of the earth's movement around the sun. The earth's axis always points in the same direction (toward Polaris, the north star) but it is inclined at 23 degrees 27 minutes away from the axis of its orbit around the sun. When it is summer in the Northern Hemisphere, the earth's axis is tilted toward the sun; in winter it is tilted away from the sun. Our location is indicated by the X's. It is evident that the sun will be high in the sky at noon at point X in the summer, and quite low in the sky at this point at noon in winter. A solar collector lying flat on the ground will obviously receive much more solar radiation in summer than in winter.

SOLAR ALTITUDE

The solar altitude is the number of degrees above the horizon at which the sun appears to be. Figure 2 shows the solar altitude at noon for different dates at 40 degrees North, about the location of this meeting.

Also represented are solar collectors with different amounts of tilt (from horizontal). The 90-degree tilt represents the usual vertical, south-facing wall. Sixty degrees is a common tilt angle for solar collectors for house heating, and would be quite good for crop drying if a surface at this angle is available. The 14-degree slope is shown because it is the same as the 3/12 roof pitch that is quite common in construction of utility buildings.

[1]Extension Agricultural Engineer, South Dakota State University, Brookings, South Dakota

The solar altitudes shown are for 40 degrees north latitude, but can be adjusted for different latitudes. For instance, if your latitude is 45 degrees north, subtract 5 degrees from each of the angles given.

The more nearly perpendicular the sun's rays are to the surface, the greater the intensity. An angle that is 30 degrees away from perpendicular results in intensity of 86 percent as much as if the angle were zero degrees, or perpendicular. If the angle is 60 degrees away from perpendicular, intensity is half as much. Also, as the angle increases, more sunlight is reflected. Beyond an angle of 60 degrees, absorbance of solar radiation drops rapidly, and is more severe for glass than for flat black paint. (1)

In Figure 2, it is evident that the best angle for a solar collector in the months of November and December is 60 degrees (this would be true also for January and February).

SURFACES TO BE CONSIDERED

Although the charts indicate that, for the fall months of October and November, the best angle for a solar collector is about the latitude plus 20 degrees (60 degrees for 40 degrees North latitude) it might be cheaper to build a solar collector on an existing surface, even if it is not at the best angle.

Figure 3 shows some surfaces to be considered. A horizontal surface is available on the ground, 30 and 60 degree slopes are possible, though not common on farm buildings. A vertical wall is available on many buildings, and the vertical cylinder is the common shape of round grain bins.

SOLAR ENERGY CHART FOR 40 DEGREES NORTH

Figure 4, taken from ASHRAE Tables (1) and (2), gives the amounts of solar energy available on a clear day at 40 degrees North latitude on surfaces with different orientations. It is about right for central Indiana, Illinois, and Ohio, northern Missouri and the Kansas-Nebraska border. (This chart can be considered almost a "mirror image" of the rest of the year, so you could write "Jan." under Nov., "Feb." under Oct. and so on. Values during the winter months are slightly better than would be indicated by this.)

The top line shows the solar energy available on a surface arranged to automatically "track the sun." It is interesting to see that it is only slightly better during the months of October and November than the next-best surface, which is one tilted 60 degrees up from horizontal, facing south. The amount of energy striking the stationary collector, tilted at 60 degrees is about 85 percent as much as that striking the "tracking" collector, so this gives an idea of how much might be gained by the extra supporting structure and mechanism required.

The 60-degree slope is better than the 30-degree slope from October through December, and both are better than a horizontal collector beginning in August. A vertical wall is better than a horizontal collector beginning in October, and is better than a 30-degree slope beginning in November. The values for a 14-degree (3/12 pitch) slope are about half way between those for the 30-degree slope and horizontal collector.

Also shown on the lower right-hand part of the chart is the solar energy on a solar collector wrapped two-thirds of the way around a vertical cylinder, such as a round grain bin. The reason for the two-thirds wrap is that this is all that will receive sunshine in the fall. The chart is based on the square footage of collector required, rather than on the part on which the sun shines. Part of it will be shaded at all times. This was not calculated for earlier in the year than September because the sun rises and sets in a more northerly position. Values in the lower-left are for a full wrap-around cylindrical solar collector. They are lower on the chart because 50 percent more collector area is required, and the values are per square foot of collector. Total heat available is probably nearly the same for a given round bin, but more collector is required to collect it.

SOLAR ENERGY CHART FOR 48 DEGREES NORTH LATITUDE

Figure 5 gives the same information as Figure 4, but for 48 degrees north latitude, which would be about right for North Dakota and northern Minnesota. Note that the values group more closely together during the fall months than on the other chart, except for the horizontal collector. Thirty-eight degree and 58 degree slopes were used because they are listed on the charts in reference (1).

Note that the vertical 2/3 wrap-around cylinder collector is about the same as a horizontal collector on October 21, and better thereafter.

WHAT DOES IT MEAN?

The charts tell only the amount of solar energy striking a square foot of given collector on a clear day. They provide meaningful comparisons _if_ the cost is about the same, per square foot, and there is plenty of surface area available on which to mount the collector. If your latitude is considerably different, you need a different chart.

The "best" surfaces might not always be the ones to use. A "poorer" surface might be used because it is readily available, or because there is not enough "better" surface to provide enough heat. A shallow roof, in addition to a wall, might be used, for instance.

Be careful about "scaling up" solar systems. Larger structures, both round and rectangular, have less solar energy striking them per bushel of capacity than do smaller ones. Calculations and comparisons should be made on designs being considered.

REFERENCES

1. ASHRAE Handbook, 1974 Applications Volume. (Chapter 59 is available as a reprint, "Solar Energy Utilization for Heating and Cooling" from Superintendent of Documents, U. S. Government Printing Office, Washington D. C. 20402. Price 70 cents. Stock Number 038-000-00188-4.)

2. Handbook of Fundamentals, American Society of Heating, Refrigeration, Air Conditioning Engineers, 1967.

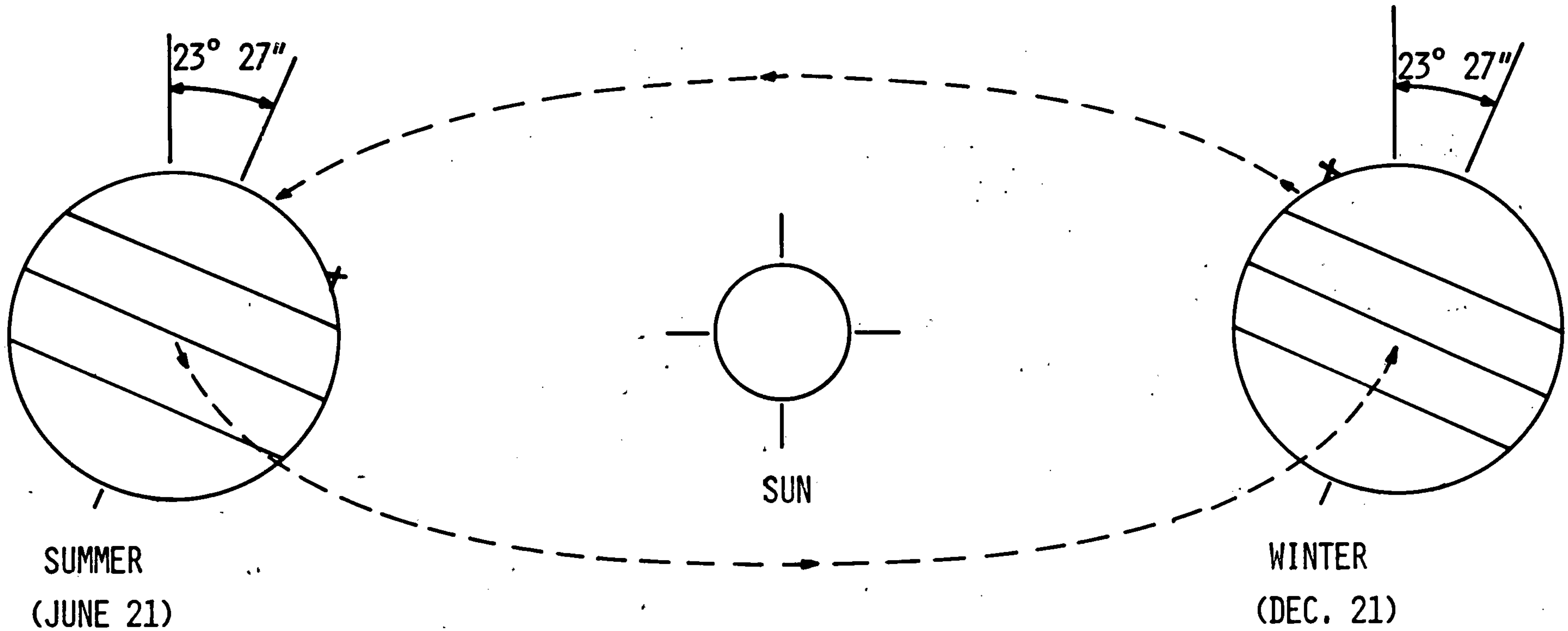

FIGURE 1. TILT OF THE EARTH'S AXIS

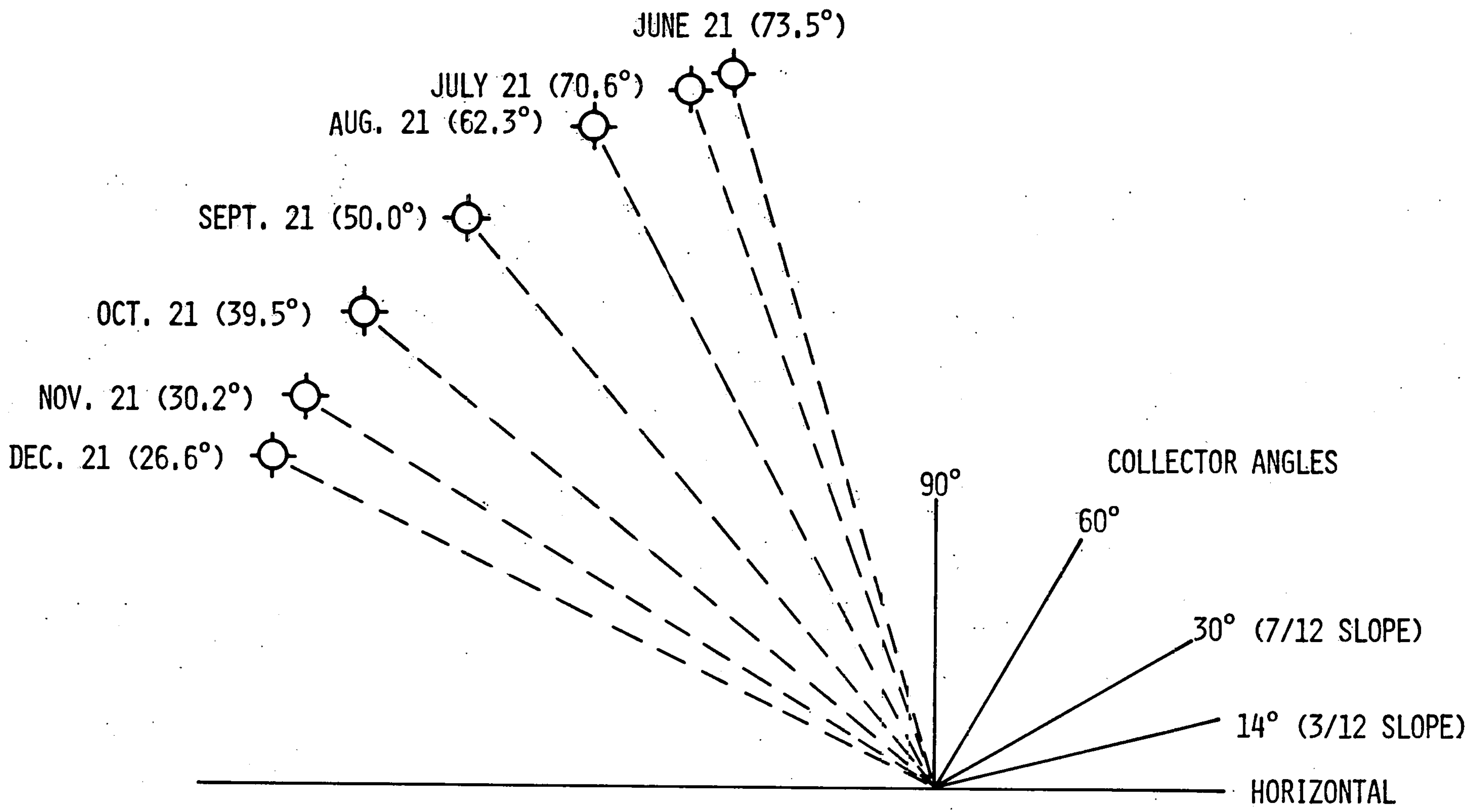

FIGURE 2. SOLAR ALTITUDE AT NOON ON DIFFERENT DATES OF THE YEAR, 40° NORTH

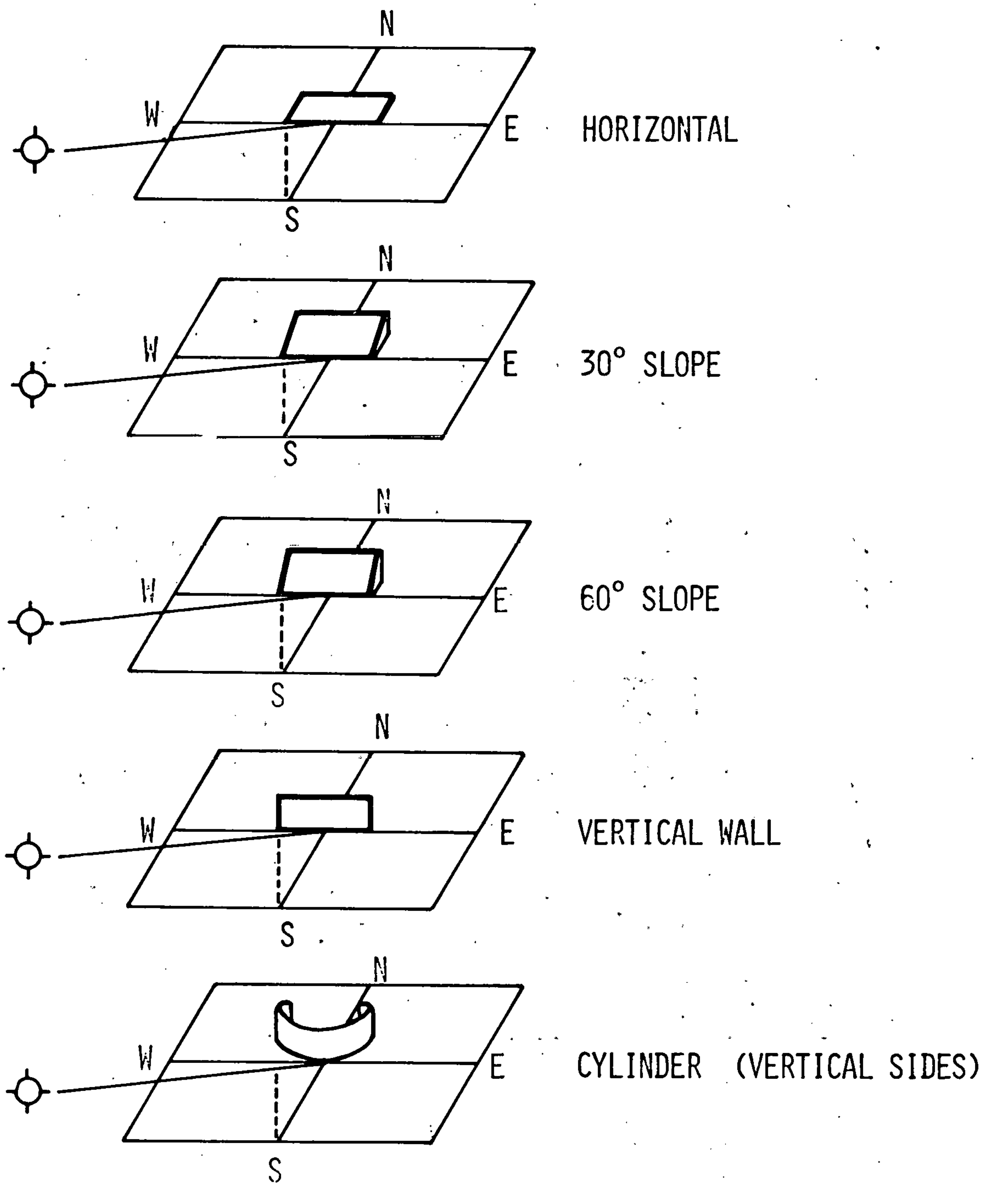

FIGURE 3. SURFACES TO BE CONSIDERED

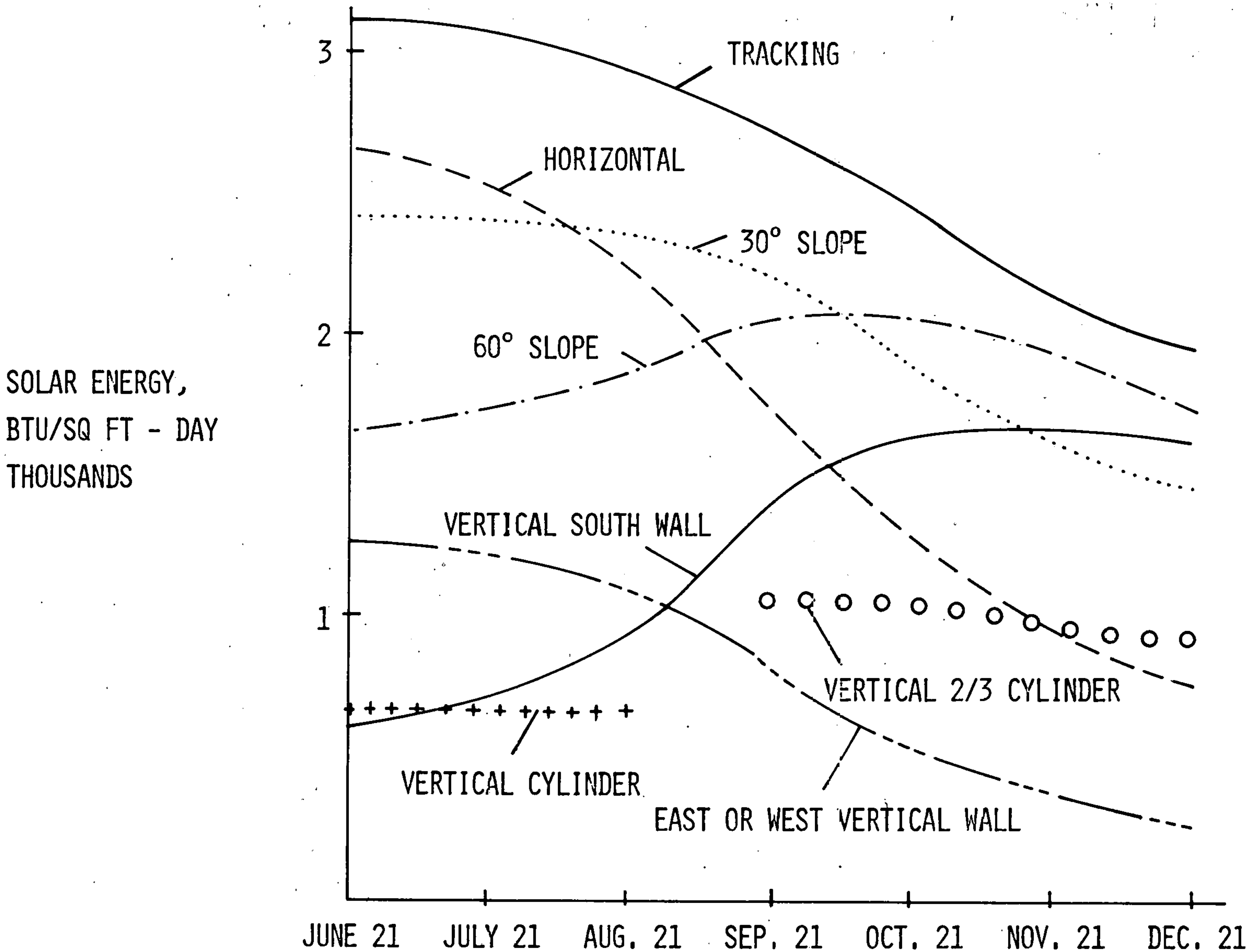

FIGURE 4. SOLAR ENERGY ON SURFACES WITH DIFFERENT ORIENTATIONS, 40° NORTH LATITUDE.

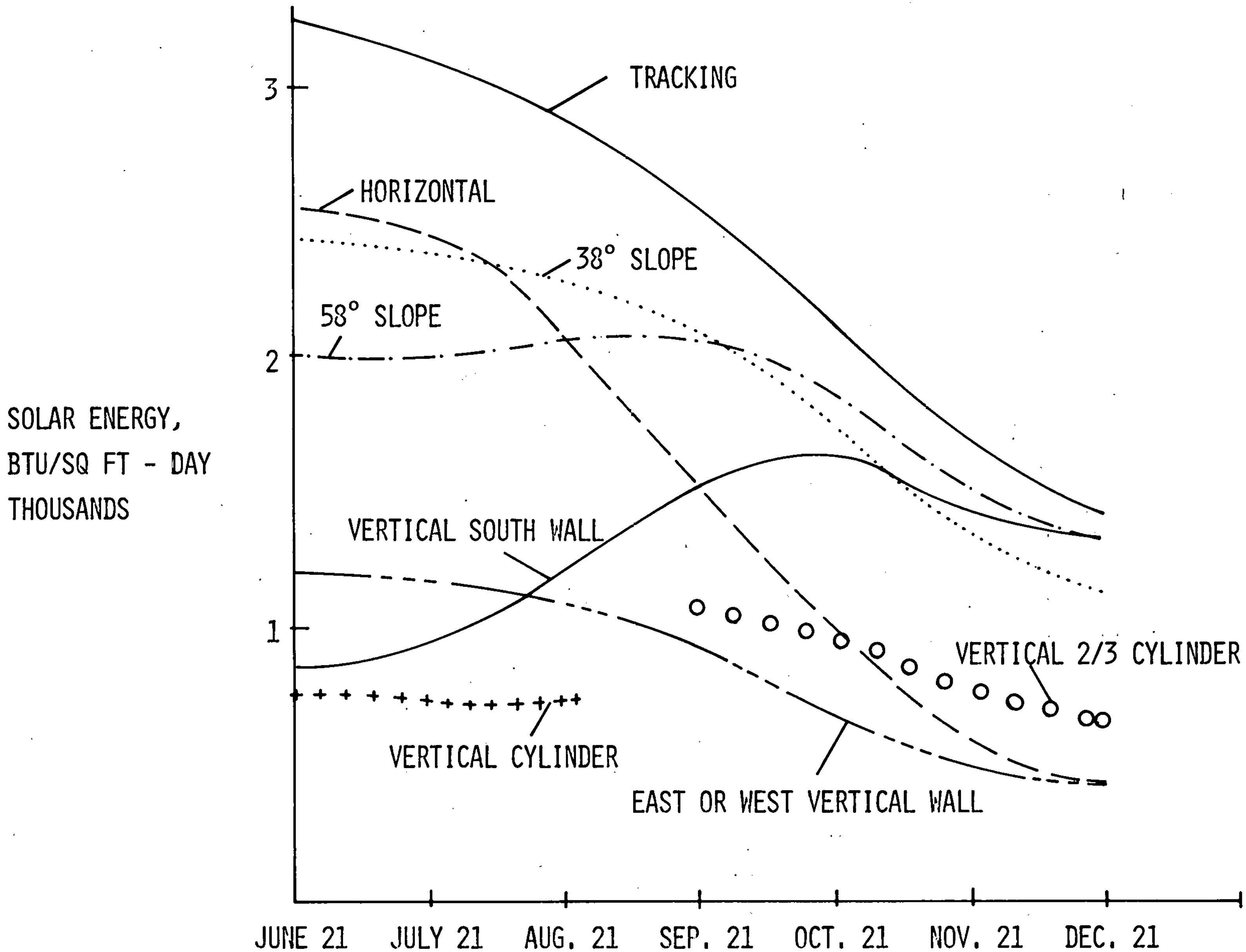

FIGURE 5. SOLAR ENERGY ON SURFACES WITH DIFFERENT ORIENTATIONS - 48° NORTH LATITUDE.

Table 1

Solar Energy Incident On Surfaces With Different Orientations, 40^{o} N. Latitude Btu/day - Sq. Ft.

	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Tracking	3100	3062	2916	2708	2454	2128	1978
Horizontal	2648	2534	2244	1788	1348	942	702
15^{o} Slope (Ave. Horiz. & 30^{o})	2541	2471	2299	1999	1808	1289	1131
30^{o} Slope	2434	2409	2354	2210	1962	1636	1480
60^{o} Slope	1670	1728	1894	2074	2074	1908	1796
Vertical Wall	610	702	978	1416	1654	1686	1646
Cylinder Area = H x D x 2				1075	1058	974.22	925
Vertical Cylinder Area = H x D x 3	670	662	686				
East or West Vertical Wall	1200	1163	1090	920	694	504	430

Table 2

Solar Energy Incident On Surfaces With
Different Orientations, 48^{o} N. Latitude
Btu/day - Sq. Ft.

	June 21	July 21	Aug. 21	Sept. 21	Oct. 21	Nov. 21	Dec. 21
Tracking	3312	3158	2898	2568	2154	1668	1444
Horizontal	2626	2474	2086	1522	1022	596	446
38^{o} Slope	2420	2386	2300	2102	1774	1336	1136
58^{o} Slope	1950	1974	2046	2070	1890	1518	1326
Vertical Wall	874	956	1208	1546	1626	1442	1304
2/3 Cylinder A = H x D x 2				1087	974	790	696
Vertical Cylinder A = H x D x 3	761	744	736				
East or West Vertical Wall	1284	1219	1074	848	556	358	274

SOLAR COLLECTOR PERFORMANCE

Gerald L. Kline[1]

INTRODUCTION

Solar energy collectors of various types were investigated for use in drying grain. The performance of 9 different solar collectors is reported for this conference.

SOLAR COLLECTOR TESTS

Pilot scale collectors suitable for low temperature grain drying were designed and constructed, Figure 1. The collectors were of the flat-plate type with air as the heat exchange medium. All collectors were 30 feet in length and 3 feet in width or diameter for an effective absorber area of 90 square feet. During the tests, the collectors were in fixed position, south facing, and elevated to the optimum angle, except the semi-circular shaped collector which had a horizontal absorber surface.

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

SOLAR COLLECTORS

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

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[1] Agricultural Engineer, USDA, ARS, NCR, Iowa State University, Ames, IA

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

The remaining three solar collectors were of the flat-plate type, rectangular in shape and incorporating suspended absorber plates. One collector incorporated a glass cover plate, corrugated metal roofing as the absorber, and insulation and plywood for the back plate and sides. The second collector incorporated corrugated fiberglass as the cover plate, deep grooved formed metal as the absorber, and insulation and plywood for the back plate and sides. The third collector incorporated clear polyethylene film as the cover plate, black polyethylene film as the absorber, and plywood as the back plate and sides.

COLLECTOR PERFORMANCE

The pilot-scale collector test results are illustrated by the example for a noon hour, Figure 2, and for a full day of operation, Figure 3. The examples are for operation on a sunny day.

The pilot-scale collector test results are summarized for noon hour operation, Figure 4, and for full day operation, Figure 5. Noon-hour collector efficiencies ranged from 14 to 83%. Lowest efficiencies were observed for bare collectors (without cover plate). Highest efficiencies were observed for suspended plate collectors with insulated back plates.

Full-day collector efficiencies ranged from 12 to 62%. For the high performance collectors, energy collected for grain drying on sunny days approximated 1500 BTU per day per square foot of collector surface area.

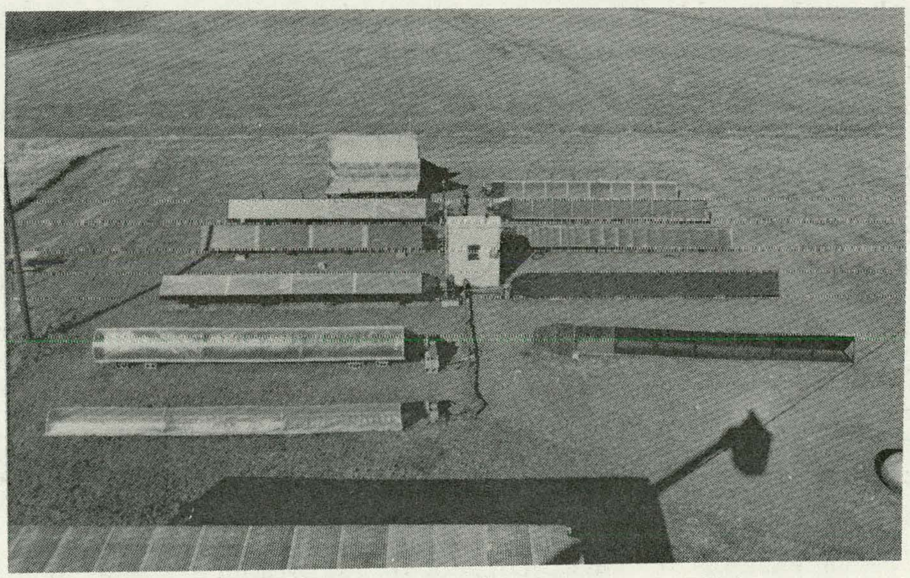


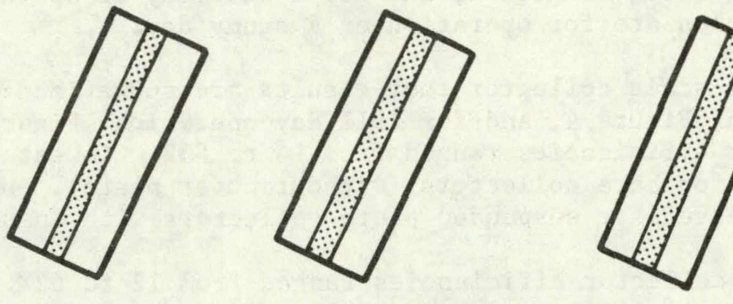
Figure 1. The pilot-scale solar collectors with the instrument shack in the center.

Air Vol 8.9 CFM/FT^2

INSOL 308 BTU/HR/FT^2

Nov. 10, 1975 - Noon
Sky Clear - Wind 15 MPH - Air Temp. 10 C

COLLECTOR			
Shape	Rectangle	Rectangle	Rectangle
Cover Plate	Poly	Glass	Fiberglass
Absorber	Poly	Corr. Metal	60^0 Metal
Back Plate	Plywood	Ply-Insul	Ply-Insul



Temp. Rise C	9.2	13.5	14.1
Energy Coll. BTU/HR/FT^2	165	241	252
Orientation Eff. %	100	100	100
Collector Eff. %	53	78	82
Overall Eff. %	53	78	82

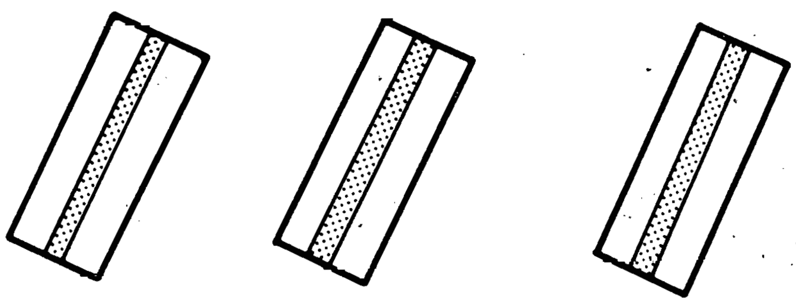
Figure 2. An example of solar collector performance for a noon hour.

Air Vol 8.9 CFM/FT^2

INSOL 2506 BTU/Day/FT^2

Nov. 10, 1975 - Full Day
Sky Clear - Wind 15 MPH - Air Temp. 10 C

COLLECTOR			
Shape	Rectangle	Rectangle	Rectangle
Cover Plate	Poly	Glass	Fiberglass
Absorber	Poly	Corr. Metal	60° Metal
Back Plate	Plywood	Ply-Insul	Ply-Insul



Ave Temp Rise C	6.6	10.5	10.7
Energy Coll. BTU/Day. FT^2	1002	1588	1618
Orientation Eff. %	83	83	83
Collector Eff. %	48	76	78
Overall Eff. %	40	63	65

Figure 3. An example of solar collector performance for a full day of operation.

SOLAR COLLECTOR EFFICIENCIES

NOON HOUR

Fall-Winter, 1975-76
21 Days, Sky Clear

South Facing
Optimun Angle
Air Flow - 8 CFM/FT^2

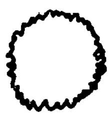
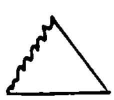
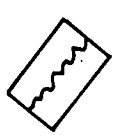
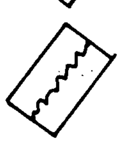
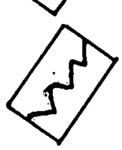
COLLECTOR				COLLECTOR EFFICIENCY %
Shape	Cover Plate	Absorber	Back Plate	
	Bare	Poly	----	17
	Poly	Poly	Ground	18
	Poly	Poly	Poly	31
	Bare	Metal	Plywood	14
	Plexiglass	Plywood	----	30
	Fiberglass	Ply-Insul	(W/Reflect)	49
	Poly	Poly	Plywood	53
	Glass	Metal	Ply-Insul	74
	Fiberglass	60° Metal	Ply-Insul	83

Figure 4. Solar collector performance for noon hour operation.

SOLAR COLLECTOR EFFICIENCIES

FULL DAY

Fall - Winter, 1975 - 76
15 Days
Sky Clear To Pt, Cldy

South Facing
Optimun Angle - Noon
Air Flow - 8 CFM/FT^2

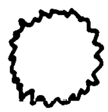
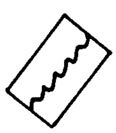
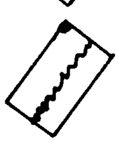
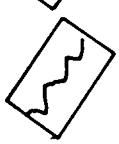
COLLECTOR				OVERALL COLLECTOR EFFICIENCY
Shape	Cover Plate	Absorber	Back Plate	%
	Bare	Poly	----	14
	Poly	Poly	Ground	12
	Poly	Poly	Poly	24
	Bare	Metal	Plywood	12
	Plexlglass	Plywood	----	22
	Fiberglass	Ply - Insul	(W/Reflect)	34
	Poly	Poly	Plywood	36
	Glass	Metal	Ply-Insul	55
	Fiberglass	60° Metal	PlY-Insul	62

Figure 5. Solar collector performance for full day operation.

PLASTIC FILM SOLAR COLLECTORS FOR GRAIN DRYING*

H. M. Keener, M. A. Sabbah, G. E. Meyer, W. L. Roller[1]

In recent years considerable improvement has been achieved in the durability of plastic materials exposed to ultraviolet radiation. The experimental use of these materials has shown their potential for use in solar heat collectors. This report discusses the characteristics of plastic film solar collectors and their potential for heating air in grain drying systems.

Characteristics of Plastic Films Used in Solar Collectors

Many types of plastic films are available for use as coverings and absorbers in solar collectors. The physical characteristics of plastic films which enhance their use in solar collectors are:

1) lightweight - a specific gravity as low as 0.91 compared to about 2.72 for glass,

2) flexibility - highly elastic and exceedingly strong which enables easy fabrication of various shaped collectors,

3) high radiation transmissivity - clear plastic films, such as polyethylene, have solar transmittance as high as 0.93 compared to about 0.9 for clear glass, and

4) high absorptivity - opaque films have absorptivity near 1.

Some disdavantages of using plastic films in solar collectors are:

1) long wave radiation transmissivity,

2) aging effects associated with ultraviolet radiation, and

3) fragility (subject to slashing or tearing).

When certain plastic films are used to cover solar collectors, the upward heat losses are greater than with glass because the plastics transmit most of the long-wave radiation, while glass is almost opaque to long-wave radiation. However, generalization is not possible since different plastic films have different transmissivities to long-wave radiation. For example, commercial clear polyethylene has a thermal transmittance of about 0.71 compared to 0.12 for the clear polyvinyl and 0.044 for the glass.

Newer plastic films are being developed which minimize some of the problems mentioned. Some commercially available films and their specific properties are listed in Table 1. Of these films, UV stabilized polyethylene

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[1]Assistant Professor, Post-Dr. Research Associate, Post-Dr. Research Associate, and Professor, Agricultural Engineering Department, Ohio Agricultural Research and Development Center, Wooster, Ohio.

TABLE 1. Plastic Films and Their Properties[1]

Type	Solar Transmittance	Thermal Transmittance	Average Durability (mo.)	Comments
Polyethylene				
Clear	0.93	0.71	10 (6 mil)	Has high thermal losses; Splits at folds; short life of 1-2 years; low in cost being .22-.43 $\$/m^2$ for 4-6 mil, respectively.
UV stabilized	0.88	0.71	18 (6 mil)	
Polyvinyl				
Clear	0.91	0.12	48 (12 mil)	Soft and pliable; tendency to be electro-static and may collect dust; life of 2-5 yrs. for UV stabilized; cost 1.1-2.2 $\$/m^2$ for 8-12 mil, respectively.
Haze	0.89	0.12		
Polyvinylflouride (Tedlar[2])	generally used as surface coating			High in cost
Glass	0.90	0.04	up to 400	7.00 $\$/m^2$

[1] Adapted from - Duncan & Walker (1973) Greenhouse Covering, University of Kentucky.

[2] Registered by E. I. Dupont DeNemours and Company, Wilmington, Delaware 19898.

film, has seen the most use because of its low cost. However, it has a very short life of less than 2 years under continuous use and probably no more than 4 years under intermittent use (e.g. during September, October and November each year).

Design of Plastic-Film Solar Collectors Used in Grain Drying

Various designs of plastic-film solar collectors have been used in grain drying research and are illustrated in Figure 1. Some of these plastic solar collectors were fabricated locally while others have been available commercially. Almost all of the commercial ones are portable, totally made of plastic films (4-10 mil, or 0.1-0.25 mm) and are air supported for easy handling and storing. Air supported films have a higher resistance to tearing during windy conditions than a 'limp' film supported by a steel or wood frame. Most of the locally designed and fabricated ones use plastic films for covering and a metal plate for the absorber. The metal absorber is usually fixed in position.

The collectors illustrated by Figures 1a and 1b were developed commercially.* The collector shown by Figure 1a consists of three layers of plastic and is referred to as a curved-cover, bicurved-absorber (CCCA). The top layer is clear, the middle layer is translucent, and the bottom layer (near the ground) is opaque. The middle layer functions partially as an absorber and partially as a second cover. Both middle layer and bottom layer form the absorber. The air-inflatable solar collector shown in Figure 1c and the frame-supported, triangular style shown in Figure 1d utilize a flat-plate plastic absorber (near the ground) and a clear plastic cover.

Inflatable tube-shaped solar collectors are illustrated in Figure 1e and 1f. They are made by placing a black plastic tube inside a slightly larger clear plastic tube. The inside tube is aligned with the outside tube either concentrically or eccentrically. Both tubes are inflated with forced air at the inlet end.

Figure 2 shows an example of a locally fabricated solar collector used in Iowa. The cover is made of clear plastic supported with bowed wood slats, the absorber is black plastic, and the collector back is plywood.

Effect of Collector Shape and Curvature

The performance of any collector is dependent on its design, shape and curvature. The cover for an air supported plastic film has a curvature associated with it, which affects the amount of incident radiation intercepted by the collector. In addition, the shape and position of the absorber affects how much radiation coming through the cover is absorbed.

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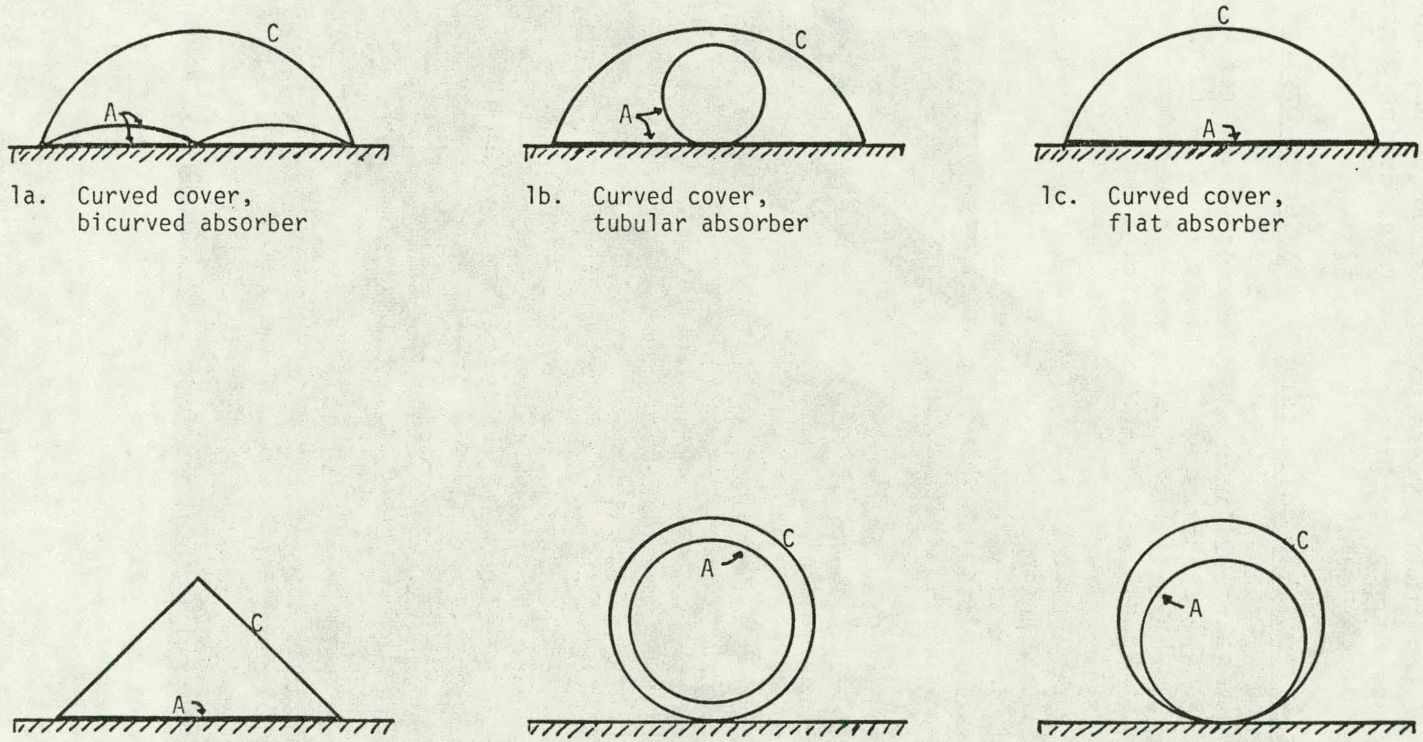
* Trademark Soloron - Mfg. by Solar Energy Products Co., Avon Lake, Ohio.



1a. Curved cover, bicurved absorber

1b. Curved cover, tubular absorber

1c. Curved cover, flat absorber

1d. Triangular

1e. Concentric tubular

1f. Eccentric tubular

Figure 1. Styles of Plastic Film Solar Collectors Used in Grain Drying - A - absorber, C - cover.

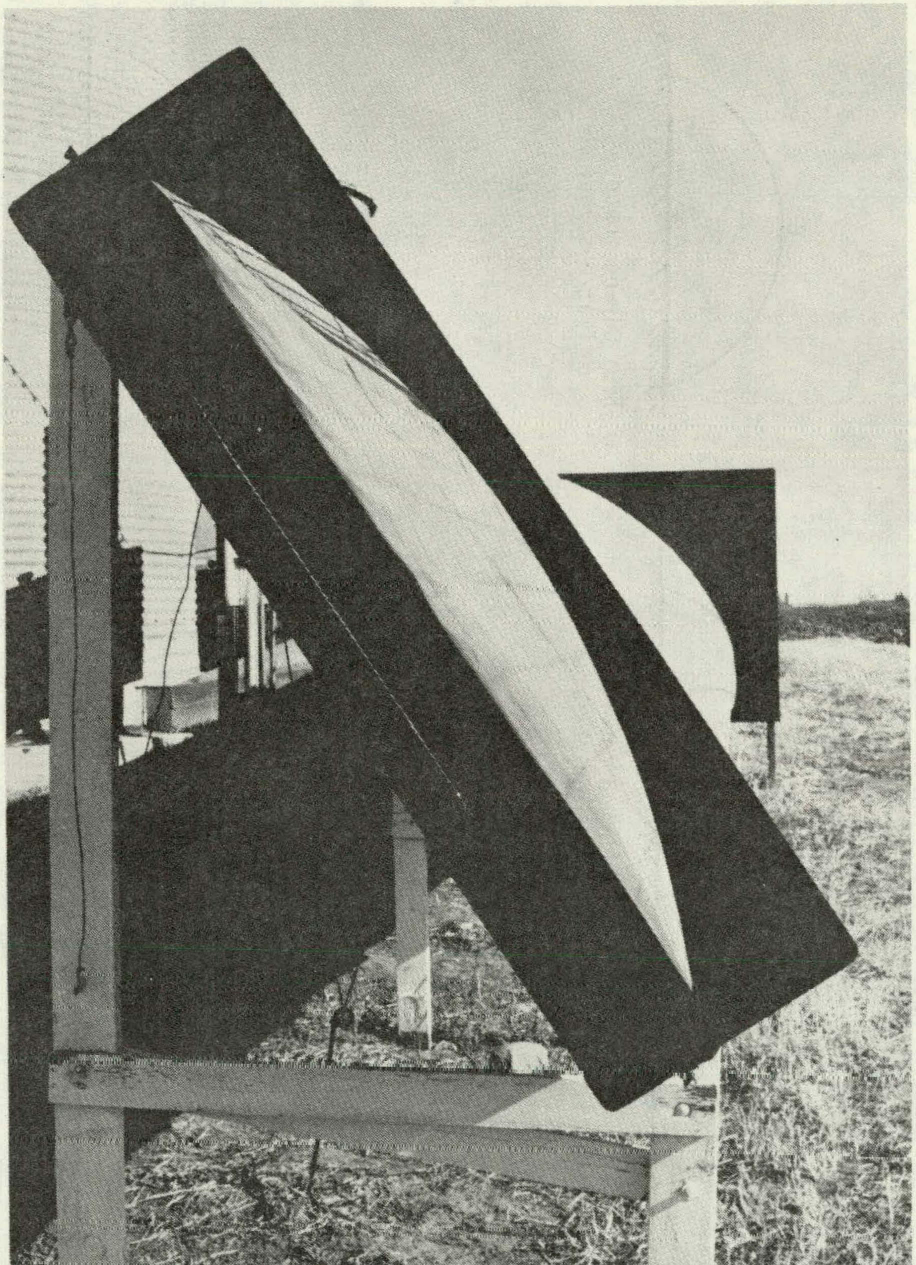


Figure 2. Curved cover flat absorber solar collector. Collector consists of a clear polyethylene cover, suspended black polyethylene absorber, and a 1/4-inch plywood back. Collector is tilted 50^{o} toward the south. Photo courtesy of Iowa State University.

The effect of the degree of curvature of the clear cover on the incident direct beam radiation striking the absorber was studied analytically by Meyer et al. (1976). Results of this study indicated that the radius of curvature has an effect on the radiation striking the absorber. There is also an interaction effect between the radius, the tilt angle of the collector and the time of the year. Figure 3 shows an example of the results obtained for Wooster, Ohio (41^{o} North latitude). For a non-tilted, CCFA collector, (Figure 1c), oriented east and west, the radius of cover curvature has only minimal effect on energy striking the absorber during October. In September, the larger radius (flatter profile) results in less reflection losses, while in November, more. For a CCFA collector tilted at the optimal angle (.87 radians or 50 degrees)* a large radius of curvature reduced reflected energy losses in the fall. Thus, tilting the collector at the optimal angle and keeping the cover as flat as possible results in the greatest interception of direct beam radiation.

Similar analysis of the eccentric tubular collector, Figure 1f, oriented east and west, indicated that the radiation coming through the cover and striking the absorber is not as sensitive to time of year as the non-tilted CCFA collector system (Figure 4). However, comparison of the daily insolation incident to absorber, between the CCFA and the tubular eccentric collectors, assuming similar areas for absorbers and for covers of the two collectors indicates the CCFA collector results in better interception of radiation at all sun angles. The difference was maximum at high sun angles and minimum at low sun angles.

For a fixed absorber radius of a tubular collector, the ratio of the cover radius to that of the absorber has a significant effect on the amount of radiation striking the absorber. The larger the ratio of cover radius to absorber radius, the higher the incident radiation to the absorber (Figure 5).

Plastic Solar Collector Performance

The performance of CCCA solar collectors (Figure 1a) has been studied experimentally in Illinois, Indiana, Minnesota (Morey, et al. 1976), and Ohio (Meyer et al. 1975). It has also been studied analytically using computer simulation techniques (Meyer, et al. 1976).

The collector is made of 10 mil UV stabilized plastic; top clear, middle translucent with an absorptivity hear 0.8 and the bottom layer opaque. It is 3.6 m wide and 25 m long (11.7 ft. x 82 ft.). The collector was designed so that about 80 per cent of the air flow rate moves through the lower path (between the middle and bottom layers) and about 20 per cent moves through the upper path (between the clear top layer and the middle layer).

*The optimum tilt angle is defined as the angle $\pi/2 - \beta_{max}$, where β_{max} is the maximum solar altitude angle occurring at solar noon.

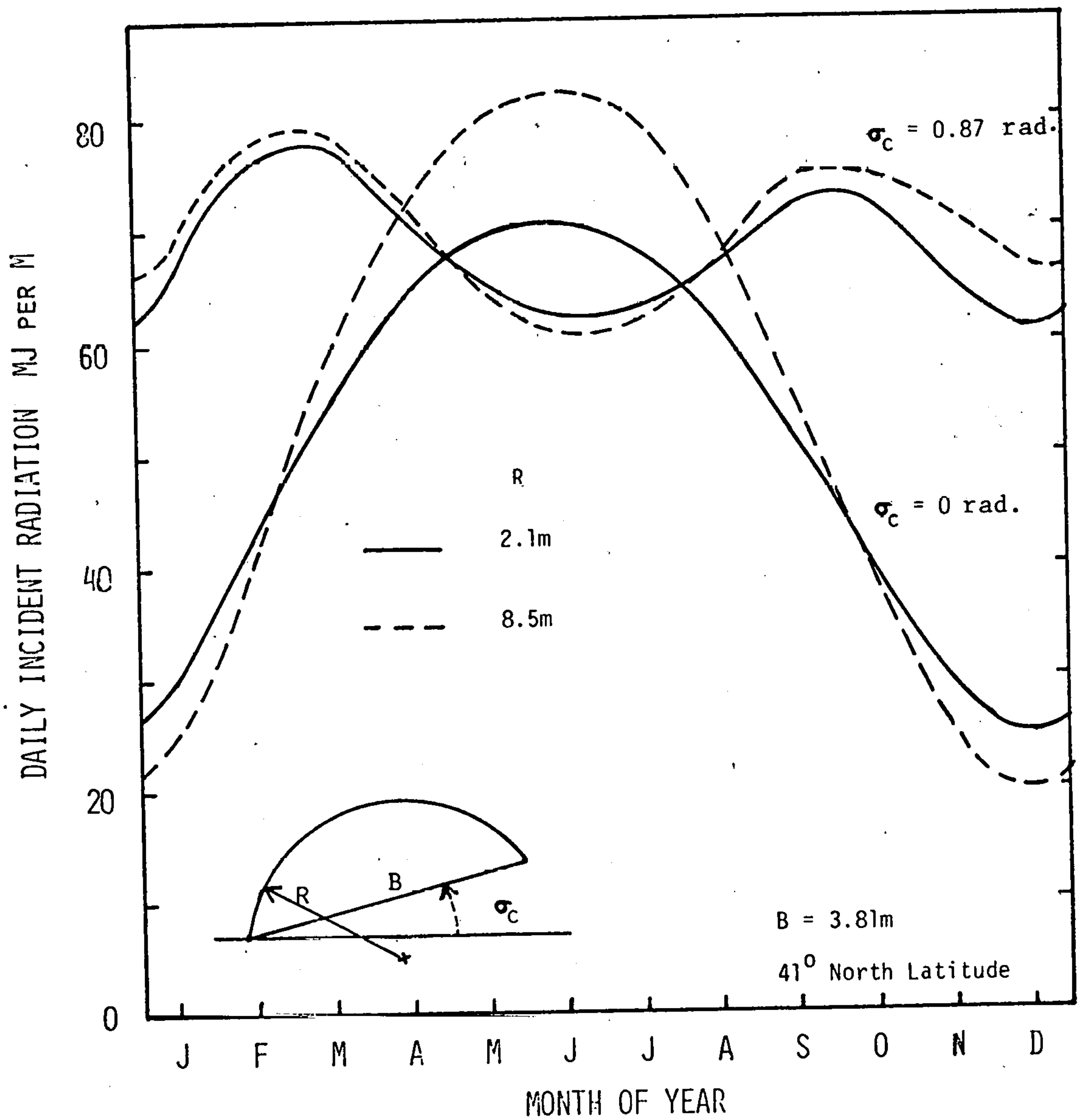


Figure 3. Total Daily Insolation per Unit Length Incident to Absorber Principle Axis of Collector oriented East-West.

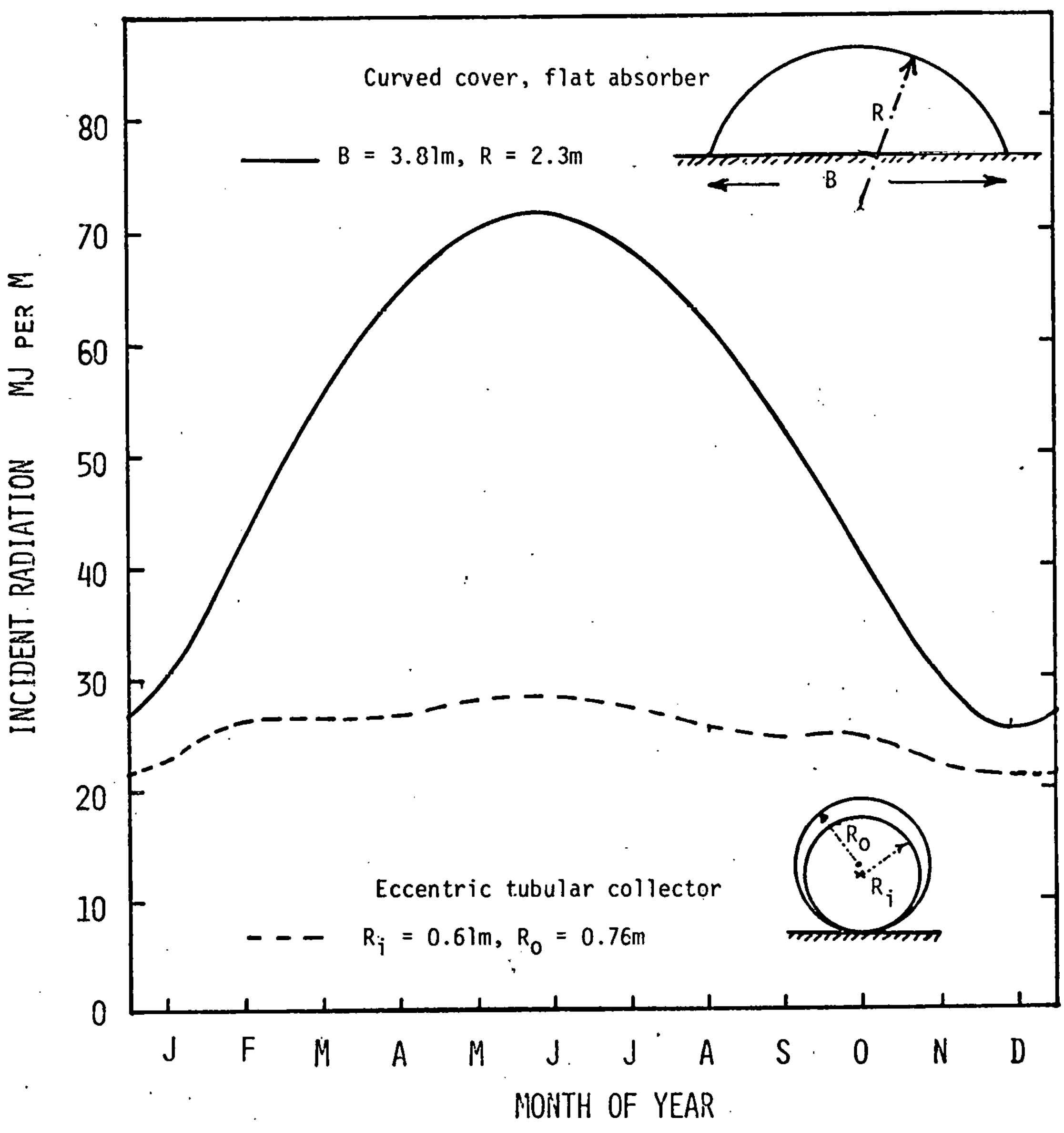


Figure 4. Total Daily Insolation Incident to Absorber of Two Collector Shapes with Equivalent Cover and Absorber Areas.

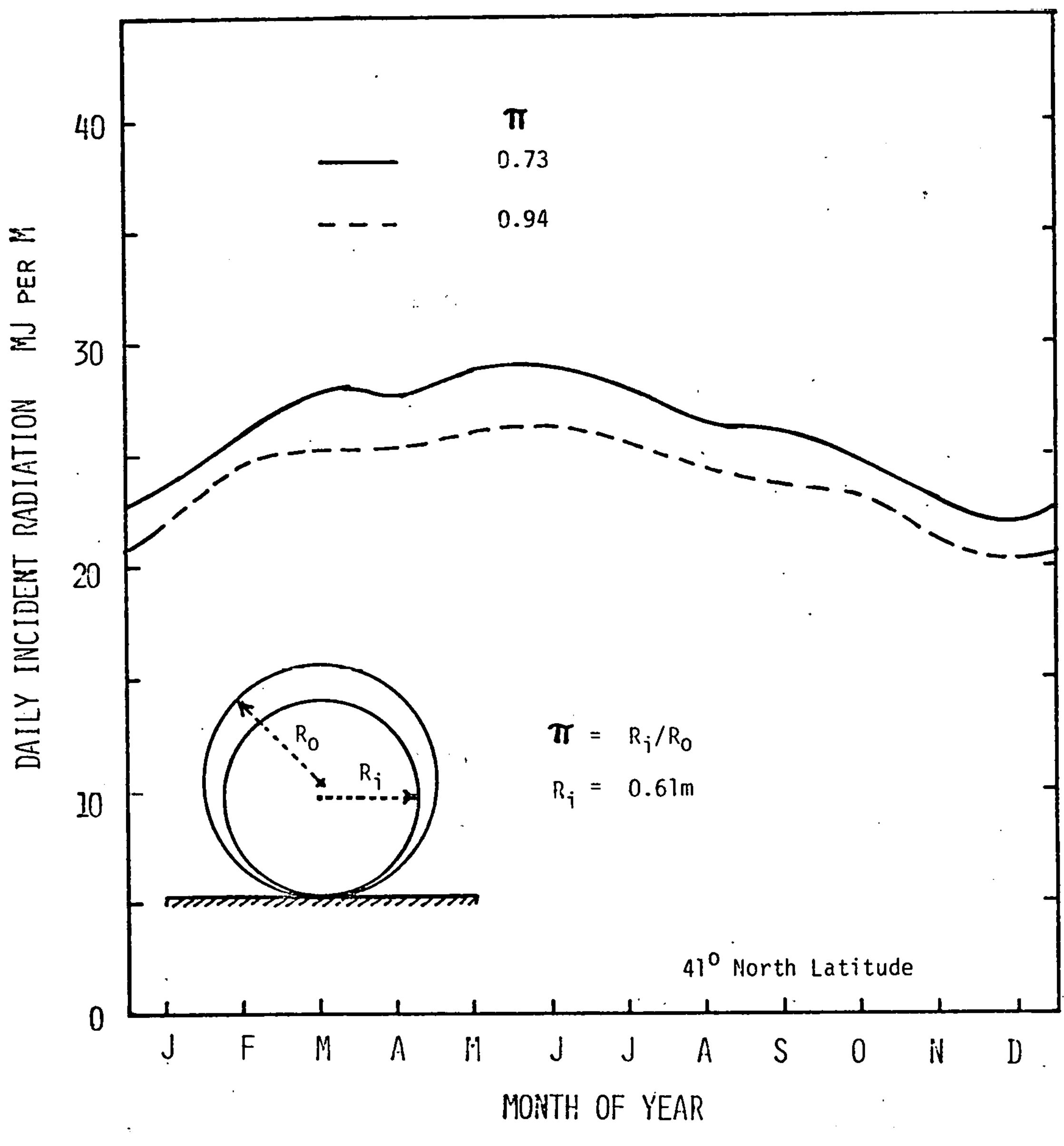


Figure 5. Total Daily Insolation per Unit Length Incident to Absorber of Tubular Collector. Principle Axis Oriented East-West.

Moreover, the ratio between the lower path and the upper path cross sectional areas is about 0.2. Therefore, the ratio between the air velocities through the upper path and the lower path is about 0.04. Considering the radiation transmissivity and the velocity ratio, almost all the useful heat gained by the collector is transferred by the air in the lower path.

Parameters studied experimentally over a 3-year period for this collector were air flow rates, orientation of the collector, the use of thermal insulation between the collector and the soil and collector life. Results of studies indicate that:

1) during late October and November, the non-tilted curved-cover, bicurved-absorber collector oriented in an east-west direction resulted in a higher collection efficiency than one oriented in a south-north direction*,

2) insulation of the collector from the soil surface resulted in a higher temperature rise during the midday, but did not improve the overall collector performance when integrated over several weeks,

3) an uninsulated collector can have large rates of heat exchange with the soil. During periods of high insolation, heat will be dissipated to the ground whereas during periods of low insolation heat may be recovered from the soil,

4) when soil temperature is above air temperature (such as in September-December) the uninsulated collector has a slight advantage over the insulated collector when total heat output is considered, and
5) collector life was about 20 months under continuous operation.

A summary of actual collector performance is given in Table 2. Computer simulation of this solar collector has been accomplished (Meyer, et al. 1976) and results for various air flow rates are given in Table 3.

Reducing air flow through the collector from 1.04 m^3/s to 0.47 m^3/s reduced heat collected by 20% in October based on simulation results. The amount of solar energy collected with this collector averaged near 350 MJ/day for October and 250 MJ/day for November. This is approximately 1.66 MJ/day per m^2 of absorber area (double layer).

Experimental studies on eccentric tubular solar collectors (Figure 1e) were done at Manhattan, Kansas (Converse, et al. 1976). The black absorbing tubes were .43 and .96 m in diameter while the clear outer tubes

* Collection efficiency = quantity of heat collected per unit area expressed as a percentage of the solar energy available.

TABLE 2. Experimental Performance of Curved-Cover, Bicurved-Absorber[a] Solar Collector at Wooster, Ohio

Air Flow Rate	Test Period	Average[b] Solar Radiation	Average Heat Gained	Eff.	Average Temp. Rise
m^3/s		MJ/day	MJ/day	%	C
1.04[c]	10/4 - 7/74	1184 ± 328	424 ± 57	35.8	4.17 ± 0.50
1.04[c]	11/16 - 23/74	616 ± 377	259 ± 83	42.0	2.50 ± 1.06
1.04[c,d]	11/16 - 23/74	645 ± 394	227 ± 68	35.3	2.06 ± 0.89
0.44[e]	9/17 - 23/75	808 ± 362	247 ± 98	30.6	5.35 ± 2.07
0.89	9/17 - 23/75	798 ± 358	368 ± 126	46.1	3.85 ± 1.31
0.77[e]	10/16 - 21/75	633 ± 473	256 ± 125	40.4	3.30 ± 1.94
0.89	10/16 - 21/75	626 ± 467	353 ± 225	56.4	3.28 ± 1.36
0.61[e]	11/23 - 27/75	433 ± 284	151 ± 95	34.1	3.81 ± 2.24

a - Trademark Soloron - mfg. by Solar Energy Products Co., Avon Lake, Ohio.
b - Based on incident radiation on a flat horizontal collector. Absorber dimensions 3.7m x 24.4m.
c - Soil temperatures rising during October and November 1974. Falling in 1975.
d - Collector oriented north-south, while in all other tests the collector was oriented east-west.
e.- Collector insulated from ground with 25 mm beaded styrofoam.

TABLE 3. Simulated Collector Output Versus Air Flow Rates[a,b]

Air Flow Rate	Max. Absorber Temperature	Max. Air Temp. Rise	Avg. Air[c] Temp. Rise	Heat[c] Collected	Collection Efficiency
m^3/s	C	C	C	MJ/day	%
.47	104.4	33.3	9.2	438	30.7
.66	90.0	27.2	7.4	493	34.6
.83	82.3	23.1	6.3	526	37.0
1.04	74.7	19.8	5.3	557	39.1

a - For Soloron air supported plastic collector, mounted in east-west orientation of principle axis, flat horizontal (tilt angle = 0) and insulated from soil surface with 25 mm thickness of beaded styrofoam.
Collector dimensions 3.7m x 24.4m.

b - Input air temperatures and total insulation values based on October 7, 1975 at Wooster, Ohio; Avg. daily inlet temperature = 15.7C, avg. daily soil temperature = 12.2C, total available insolation = 1424.4 MJ. Wind run = 100.4 Km per day.

c - 24-hour operation

Ref: Meyer, et al. 1976.

were .51 and .99 m. Collector length was 30.5 m and air flow was approximately 0.59 m^3/s for both collectors. Results of test data for the tubular solar collector are given in Table 4.

The amount of solar energy collected in eight tests by these collectors averaged 144 MJ/day. Output for the .86 m diameter collector averaged about 1.67 MJ/day per m^2 of absorber area.

Another plastic collector which is commercially available has a clear polyethylene cover over a triangular, wire frame with black polyethylene film as the absorber forming the floor (Figure 1d). Air is drawn through the collector and heated on its way to the fan on the drying bin. This collector design has been used on farms in Iowa.

Operational experience with plastic film collectors suggest problems with snow loads collapsing collectors, stress cracking of covers during below-freezing weather, and mechanical damage occurring to covers because of man or beast. This was especially true of the semi-circular collector. Based on field results, plastic film solar collectors would be operational only until about December 1 for most of the Midwest. Over the first 15 months of continuous use in Ohio, the collectors were relatively maintenance free (exceptions were a burned-out fan motor and vandalism to the collector cover of one unit). However, since then, maintenance has become a problem with the major concern being keeping the outer cover intact on the collector. Minnesota noted improvement in collector efficiency when the collector was located next to a structure which would act as a reflector.

Cost Benefit Ratio of Plastic Solar Collectors:

The cost of using a solar collector includes fixed cost plus operating expenses. Cost data reported by workers at Kansas for the circular collectors is about 3.77 $\$/m^2$. The cost of the CCCA collector (commercially made) in 1974 was about 17.22 $\$/m^2$ plus cost of the fan to operate the system. Cost data of the plastic film alone ranges from under .43 $\$/m^2$ of film area for 6 mil UV stabilized polyethylene film up to 3.23 $\$/m^2$ for 12 mil vinyl with a 1 mil tedlar* coating. The power to operate the system varies depending on air flow rates used, the style and the dimensions of the collector.

Calculation of the cost of heat energy output from a solar collector is given by

$$c_q = \frac{C_s + \int_o^T r_s C_s dt + \int_o^T c_p \, P \, dt + \int_o^T c_1 w_1 \, dt}{\int_o^T E_o \, dt} \quad (1)$$

* Trade name of the E. I. Dupont DeNemours and Company, Wilmington, Delaware 19898.

where

c_q = cost of energy, \$/MJ

C_s = cost of system, function of P, \$

r_s = annual rate charge against investment

c_p = cost of energy input, \$/MJ

P = energy input per hr., MJ/hr

c_1 = cost of labor, \$/hr

w_1 = labor required per hour of operation, man-hours/hr

E_o = energy output, function of P, MJ/hr

T = life of system, hr

Based upon field data a 10 mil vinyl UV stabilized plastic film collection system could be expected to last over eight seasons if put up at the end of September and removed at the end of November. This would represent a total expected life of about 11500 hours. For the installation and removal of a plastic solar collector of about 90 m^2 between 10 and 20 man hours could be expected per unit per season (assumed 15 man hours). Annual charge against investment to cover cost such as insurance, interest and repairs is assumed to be 12% of the investment per season, or 96% of the collector cost over its lifetime.

Substitution of these values in equation 1 gives

$$c_q = \frac{1.96\ C_s + c_p \int_o^T P\ dt + 120c_1}{\int_o^T E_o\ dt} \qquad (2)$$

Using computer simulation, heat output $\int E_o dt$ versus energy input $\int P\ dt$ was evaluated for a 90.1 m^2 collector and is given in Figure 6. Results indicate that solar energy collection for the system approaches a maximum at about 57 MJ/day input (air flow rate, 1.42 m^3/s).

Letting $C_s = A + (175 + 75\ HP_{fan})$, in which A is the cost of the collector, the cost of the heat output is given by

$$c_q = \frac{1.96A + 343 + 147\ HP_{fan} + c_p \int_o^T Pdt + 120c_1}{\int_o^T E_o\ dt} \qquad (3)$$

TABLE 4. Experimental Performance of Eccentric Tubular Solar Collector at Manhattan, Kansas.[a]

Absorber Diameter m	Tube Ratio Ri/Ro	Test Period	Avg. Solar[b] Radiation MJ/day	Avg. Heat Gained MJ/day	Eff. %	Avg. Temp. Rise C
		1974				
0.86	0.87	9/23 - 10/13	482	146	30.4	1.9
0.86	0.87	11/16 - 12/13	392	116	29.5	1.6
0.86	0.87	11/25 - 1/15	438	159	36.3	1.9
		1975				
0.43	0.85	9/17 - 10/9	276	171	61.8	2.5
0.86	0.87	9/24 - 10/6	546	179	32.7	0.9
0.43	0.85	10/15 - 10/24	279	131	47.1	1.5
0.86	0.87	11/18 - 12/11	416	109	26.1	1.2

a - Ref: Converse, Foster and Sauer, 1976.

b - Calculated on basis of flat solar collector tilted at optimal angle toward the sun, length of collector 30.5 meter. Air flow rate was approximately 0.59 m^3/s; orientation of collectors was east-west.

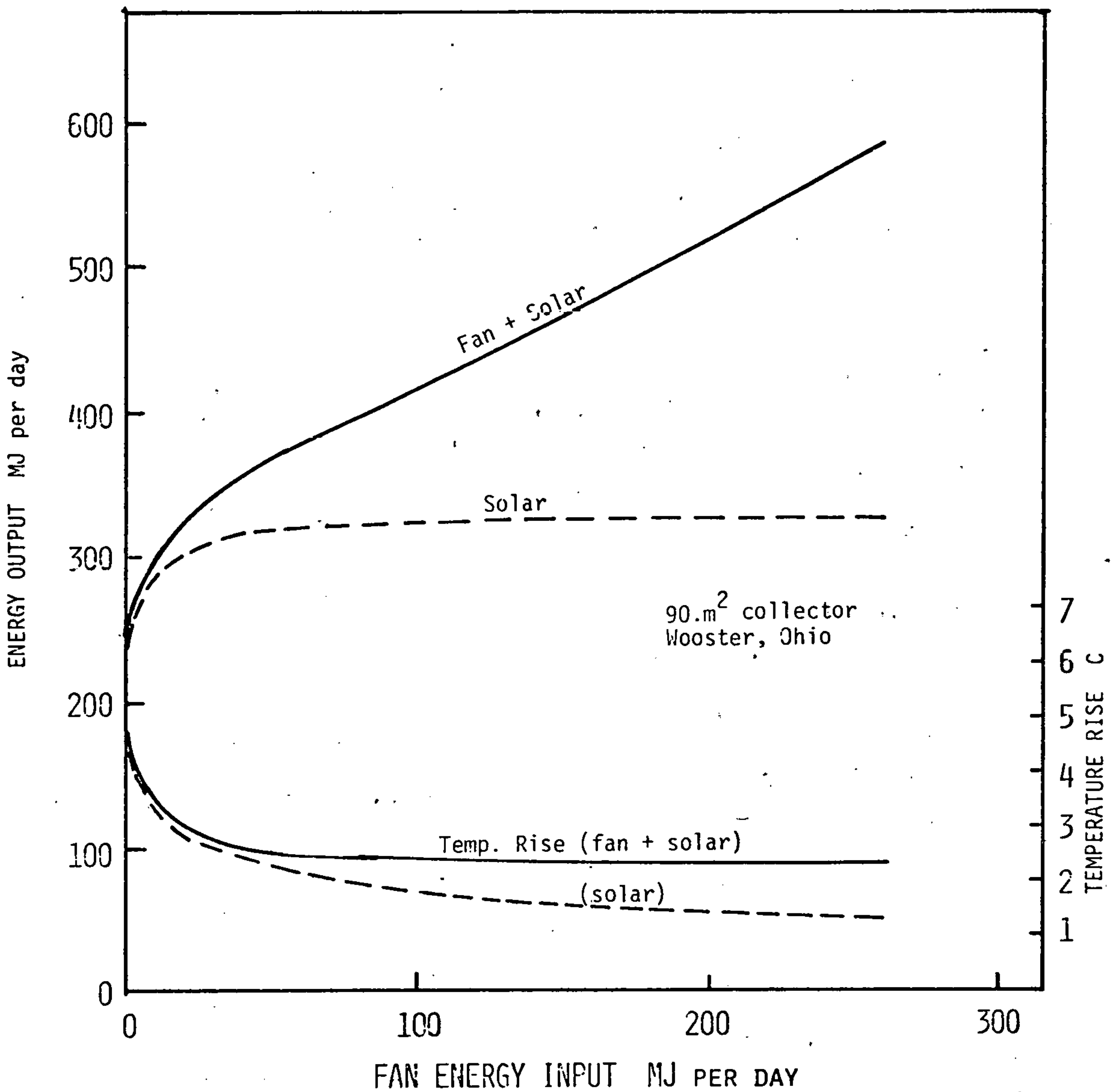


Figure 6. Energy Output vs. Fan Energy Input for a 90 m^2 Curved Cover Bicurved Absorber Solar Collector. Based on average October-November Weather Data (14 year average) at Wooster, Ohio

Solutions of this equation are given in Table 5 for various values of A, assuming electrical power cost 4¢/kwh (1.11¢/MJ). Minimum cost of heat when A = 0 would be 0.55¢/MJ which is equivalent to about 53¢/gal for propane. A plot of minimum heat energy cost from the solar collector versus collector cost is given in Figure 7. The breakeven point when electrical power cost 4¢/kwh is a collector cost of $420 (4.66 $/m^2). Using an electrical power cost of 8¢/kwh, the breakeven point increases to a value of $1300 (14.43 $/m^2). The 1976 electrical power cost range as high as 4.5¢/kwh in Ohio while propane cost was about 43¢/gal (0.45¢/MJ). Based on the current cost of propane (and ignoring equipment cost for using propane) it would remain as the lowest cost source of heat for grain drying.

CLOSURE:

The use of plastic film collectors for grain drying in future years appears feasible when one considers that 1) as much as 1000 m^2 or more of collector area is required per drying installation, and 2) the life of plastic film collectors could be doubled at little cost through design modifications and management practices.

Keener, et al. (1975) reported the use of solar heated air for batch grain drying and has proposed a system design for handling 40,000 bushels of grain using plastic film collectors. Figure 8 is an example of such a system using 1080 m^2 (.27 acres) of collector area. Using plastic film collectors of CCCA type or eccentric tubular type for this system allows the grain operator to build his grain drying system in the most favorable location, doesn't place a heat load on a fixed structure (such as machinery shed) during summer months, and minimizes duct work needed to convey air from the collector(s) to dryer fan. All of these factors can lead to low operating cost because of efficient flow of grain and air into and out of the grain handling systems.

To improve the life of plastic film solar collectors and reduce their cost the following recommendations are made:

1) maintain in sod the area adjacent to the grain bins where the solar collectors will be installed. This allows hardware for securing collectors to remain in place thus minimizing setup time for collectors each year while at the same time providing a surface suitable for collectors to lie on without fear of damage.

2) do not use insulation under plastic film solar collectors which are in contact with ground,

3) collectors should be made of vinyl so that they can be folded without damaging film. Initial cost will be higher, but improved performance offsets cost.

4) use collectors only during late September, October and November. Removal of collectors at end of November and putting in storage until following fall drying season can increase life of collectors from two years (full exposure) to over eight years, and

5) design collector such that outer cover can be replaced at end of its useful life.

Results of studies to date suggest that only outer cover would have deteriorated at end of eight seasons. Thus, making the outer cover replaceable would increase total life of collector system with little increase in system maintenance cost.

TABLE 5. Cost of Heat Energy from a Solar Collector[1]

Air Flow	Energy Input[3]	Energy Output	Collector Cost, $/unit 0	400	800	1600
m^3/s	MJ/day	MJ/day	¢/MJ			
.47	2.10	248	.603	1.261	1.919	3.235
.71	7.08	288	.548	1.116	1.683	2.819
.94	16.79	318	.545	1.059	1.574	2.602
.42	56.62	377	.626	1.059	1.492	2.357
1.88	134.20	461	.780	1.135	1.489	2.197
2.36	262.11	586	.960	1.238	1.516	2.073

1 - Based on 90.1 m^2 semicircular collector located at Wooster, Ohio. Operated only during months October - November.

2 - Upper practical limit on air flow rate assuming collector cannot stand more than 1 in H_2O pressure.

3 - Assumes electrical cost of 4¢/kwh - (note: 1 kwh = 3.6 MJ; 1 MJ = 948 BTU).

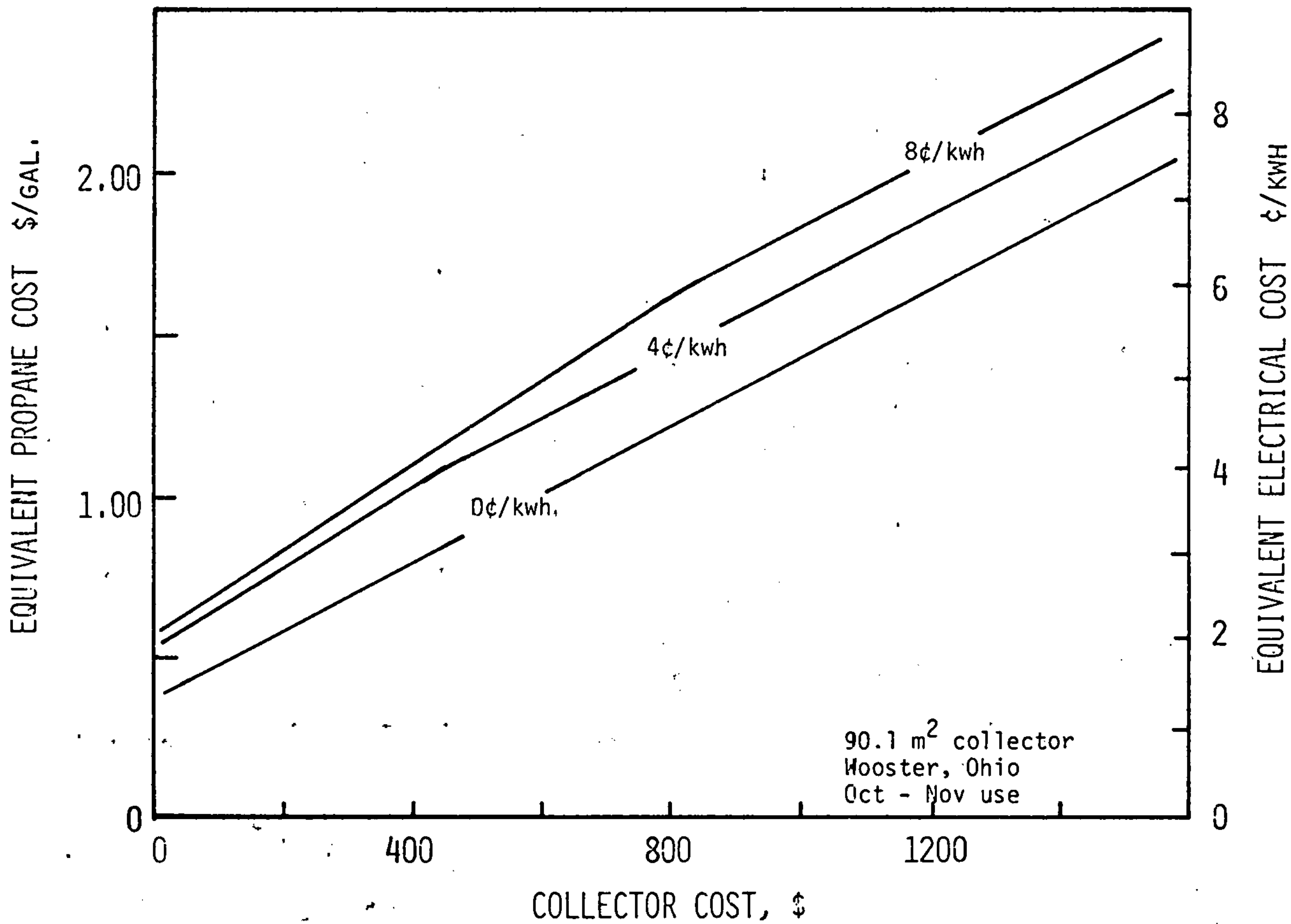


Figure 7. Cost of heat energy from a solar collector versus cost of solar collector.

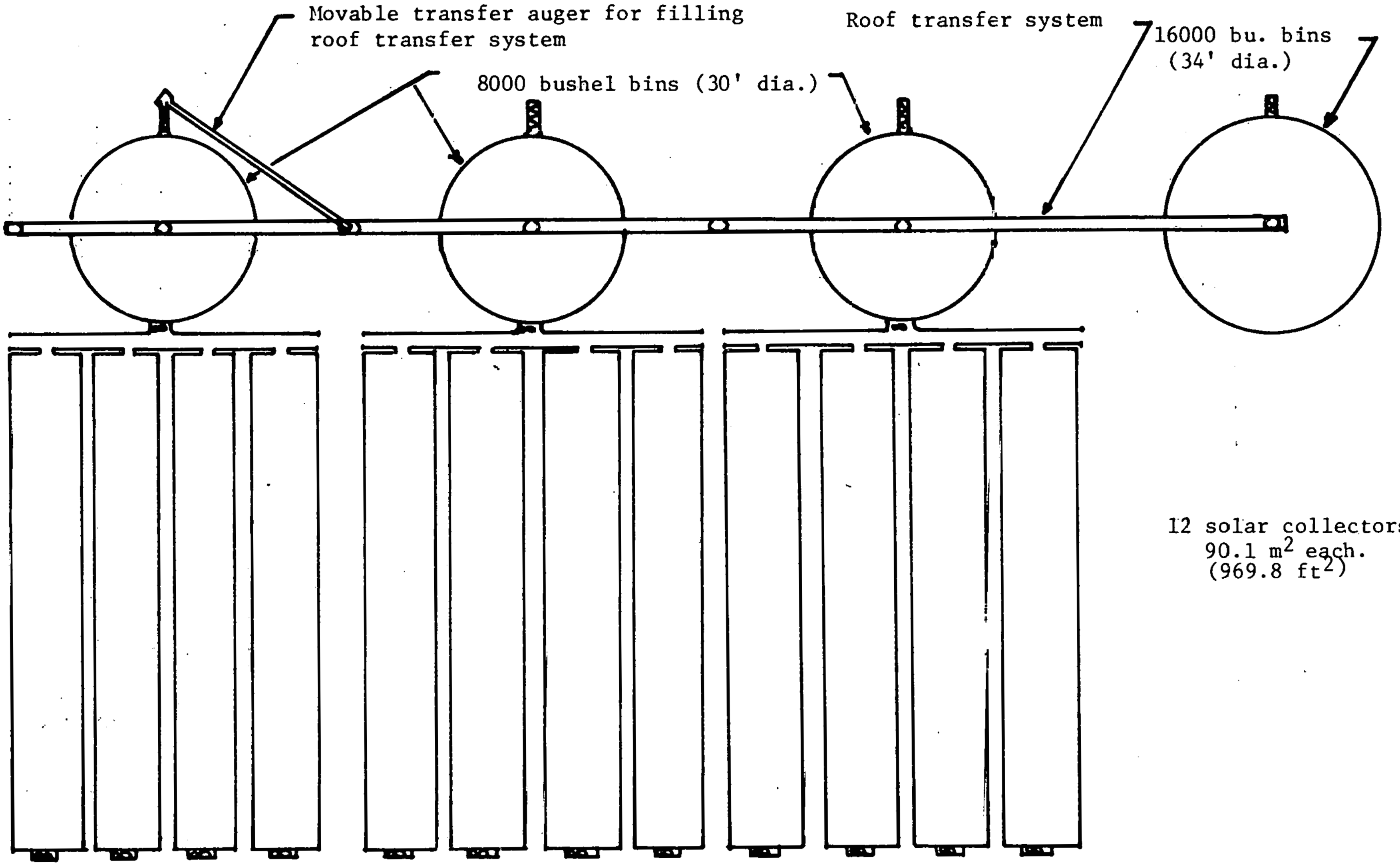


Figure 8. Solar batch grain drying system - minimum drying capacity 800 bushels/day of corn. Drying corn from 25% to 15% moisture (w.b.), storage capacity 40,000 bushels.

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BIN SIDEWALL COLLECTORS

William H. Peterson[1]

Bin sidewall solar collectors deserve serious consideration for use in crop drying because:

1. They are likely to be less costly to build than free-standing separate collectors of optimum slope, since a structure is generally already available on which to mount the collector.
2. They are out of the way and do not take space out of often-crowded farmsteads as would separate solar collector structures.
3. They can be made to work on both rectangular and round bins.
4. A south-facing vertical collector is likely to receive more solar energy per square foot on a clear day in the fall than most typical roof slopes or a horizontal surface in the midwest.
5. They offer the opportunity of increasing solar energy by addition of a reflector laid on the ground. (But if this is done, point No. 2 above is compromised.)

Of course, sidewall collectors do require spacing from any shading structure to the south of 2 to 2½ times the height of the structure; more to the southeast and southwest is desirable. Also, if doors or windows are desired in the collector area, there are problems to solve.

FIRST "WRAP-AROUND SOLAR COLLECTOR" BIN

In 1973, Myron Pedersen, who farms near Arlington, South Dakota, expressed an interest in using solar heat in his 3000-bushel low-temperature drying bin. Kingsbury Electric Cooperative, his power supplier, offered to furnish materials, and East River Electric Power Cooperative recruited a "work crew" to build the solar collector.

The solar collector was constructed by mounting wood strips on 2' centers, built up from three layers of 1" by 2" wood strips mounted horizontally around the southern two-thirds of the bin, mounting aluminum sheets over the strips (they were used offset press-plates, reasonably priced) painting the sheets black, and mounting three more layers of wood strips and stretching a sheet of clear polyethylene over the top. This formed the channels to bring air around the bin, on both sides of the black sheet, and into a tunnel on the northeast side of the bin.

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[1]Extension Agricultural Engineer, South Dakota State University, Brookings, South Dakota

We used polyethylene sheet because it was low in cost, although we did not expect it to last more than one season. This bin is shown in Figure 1.

I should note here that we had considerable difficulty in bending the 1" by 2" pine strips around the 18-foot diameter bin without breaking them. By a number of means, such as soaking them with water and notching the backsides with a saw, we were able to get them mounted, but it became evident that a "better way" should be devised.

The solar collector produced about a 10 degree temperature rise at noon on the airflow of the 7½ hp drying fan, which was about the same temperature rise as produced by the 19.2 kilowatt electric heater. The drying fan ran from October 23 to November 20, to dry 2800 bushels of shelled corn from 20 percent to 14 percent moisture. The electric heater was not used. Energy used was 4794 kilowatt-hours, or 1.7 kilowatt-hours per bushel. Temperature and relative humidity were near normal for South Dakota during the drying period.

One of the difficulties with this solar collector was the sagging of the polyethylene between the supporting strips. This restricted airflow and increased the pressure drop, which was measured at about 3/4 inch of water when the bin was filled with shelled corn.

In 1974, the polyethylene cover having deteriorated beyond usefulness, Myron Pedersen replaced it with flat fiberglass sheets, of the type sold by mail-order catalog houses for greenhouse use. The performance of the solar collector was as good as it had been with the polyethylene sheet. This bin is shown in Figure 2. The sagging and pressure drops experienced with the polyethylene cover were much improved, with pressure drop through the collector of under ½ inch of water.

It was suspected that the collector might be "leaking" air in at the overlaps of the vertically-mounted 4-foot wide fiberglass sheets, but air velocity measurements at inlets and outlets indicated that not more than 15 percent of the airflow was contributed through leakage.

In 1974 and 1975 we were able to secure data from a low-temperature drying bin on the Converse farm nearby which was identical to the Pedersen bin, except for the solar collector. This provided us with a comparison, or "control" with which we could make comparisons of energy efficiency. In 1974 the solar bin used 26 percent less energy for drying, on a per-bushel, per point of moisture basis, and in 1975 it used 55 percent less energy. The apparent saving was $106 with electricity at 1.75¢/kwh. The 1974 season was considerably more favorable for drying than normal; some farmers dried with natural air. The 1975 season was more near-normal, but still more favorable for drying. The data are summarized in Tables 1 and 2.

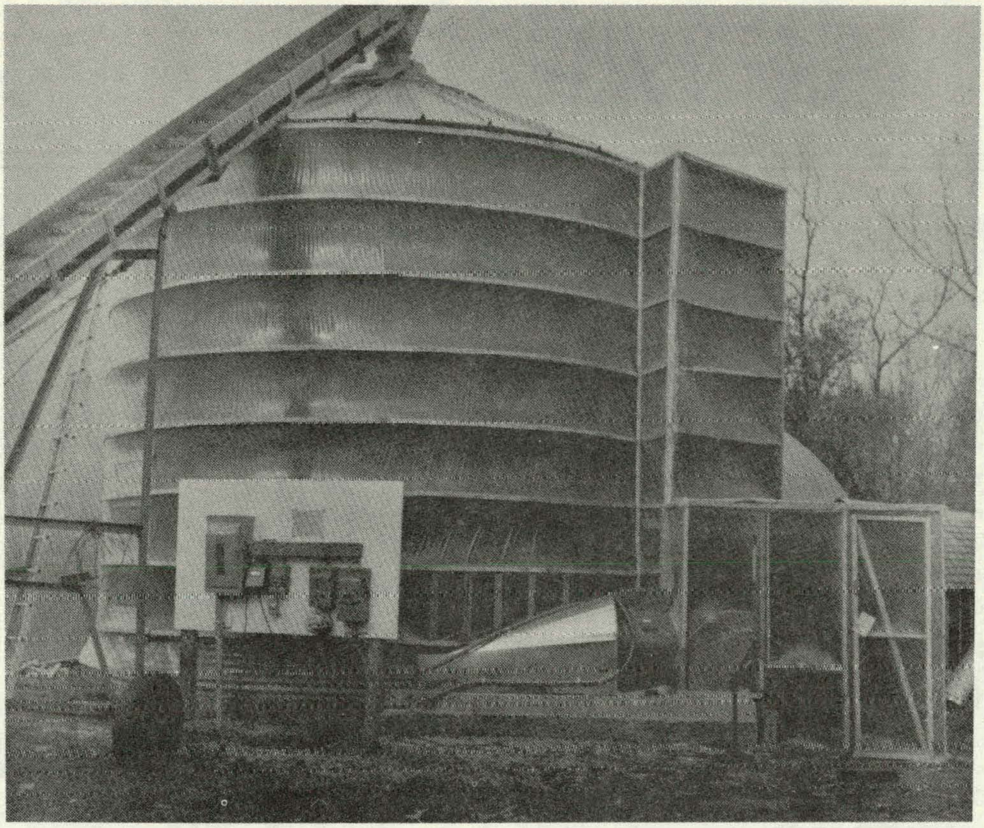

Figure 1. Myron Pedersen solar drying bin, 1973.

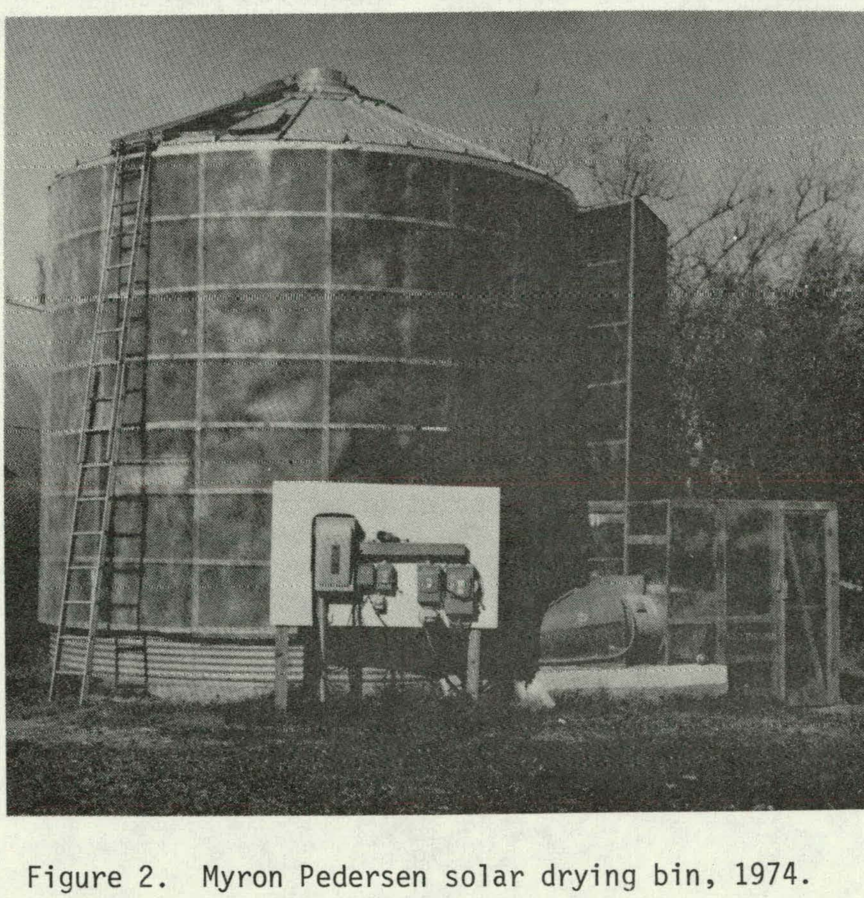

Figure 2. Myron Pedersen solar drying bin, 1974.

Table 1. Comparison of Selected Data, Pedersen Solar Bin and Converse Control Bin. 1974

Initial:	Pedersen Solar Bin	Converse Control Bin
Ave. Moist.	18.16%	20.04%
Oct. 23		
Ave. Moist. Content	12.77	13.46
Moist. Removed - Pts.	5.39	6.08
Bushels	2950 (103 cu.M)	2030 (71.4 cu.M)
KWH-Fan	1964	1844
KWH-Heater	0	233
KWH-Total	1964	2067
KWH-Bu. (35.24 l.)	0.665	1.018
KWH/Bu.-Point	0.123 (26% Less)	0.1674
BTU/Lb. Water Removed	635 (352 cal/gm)	766 (431 cal/gm)

Weather Conditions, Departure From Normal

Temperature	9.5 F	11.3 F
Relative humidity	-15.6%	-15.9%
% possible sunshine	22.3%	19.2

Table 2. Comparison of Selected Data, Pedersen Solar Bin, Converse Control Bin, and Redfield Solar Bin. 1975

	Pedersen Solar	Converse Control	Redfield Solar
Starting Date	Oct. 14	Oct. 21	Nov. 3
Finishing Date	Nov. 10	Nov. 17*	Nov. 24
Initial Moisture	22.05	20.0	22.2%
Final Moisture	13.6	15.78	14.9
Moisture Removed, Points	8.45	4.22	7.3
Bushels	3053	3053	1000
KWH-Fan	4869	3474	1757
KWH-Heater	0	2014	621
KWH-Total	4869	5488	2378
KWH/Bu.	1.59	1.79	2.37
KWH/Bu.-Point	0.1887	0.424	0.32
BTU/LB. Water Removed	930	2081	1570
Weather Conditions, Departure From Normal For October - November			
Temperature	+5.5°F	+2.6°F	-4.8°F.
Relative Humidity	-3.3%	-2.3%	+1.1%
% Possible Sunshine	+7.4%	+5.7%	+2.7%

* Corn was not dried to desired moisture on this date, but drying was discontinued due to cold weather.

REDFIELD 5-COLLECTOR BIN

In the fall of 1974, with the assistance of ERDA funds managed through USDA, we constructed five different types of solar collectors on a bin located at the University farm near Redfield, South Dakota, to make comparisons. This bin holds 1000 bushels, uses a 3 hp fan and an 8-kilowatt electric heater.

Instead of trying to bend the wood strips around the bin, we had them prefabricated to the proper curvature by a manufacturer of laminated wooden rafters. This was much more satisfactory than the method we had used before.

The top collector is a suspended-sheet type, polyethylene-covered, like Myron Pedersen's, the second one is the same, except it is covered with corrugated clear fiberglass, the third one is a bare-sheet collector, made from used press-plates and hand-corrugated in a sheet metal brake, the fourth one down is bare-sheet type, of corrugated aluminum roofing, and the bottom collector is a bare-sheet type of corrugated steel roofing. The bin is shown in Figure 3. Performance is described in Table 3.

Collecting of temperature data in 1974 and 1975 on this bin convinced us that, while the bare-sheet collectors may not be more efficient than those with transparent covers, in the situation where we were using them they were almost as good, and did offer advantages in cost and probable life. Data on the Redfield solar bin is compared with the Pedersen bin and the "control" bin in Table 2. It should be noted that drying at Redfield was done later in the year, and electric heat was needed to get the corn dry enough, so more energy was used. A full report was made by Peterson and Hellickson (1).

PROTOTYPE SOLAR BIN

In the fall of 1976, with the help of funds from the Federal Energy Administration through the State Office of Energy Policy, the Southeast Experiment farm corporation, and a number of other cooperators, a prototype commercially-built solar drying bin was constructed at the SDSU Southeast Experiment Farm, Beresford, South Dakota (Figure 4).

This project has two objectives; one is to inform farm operators in the area about methods of drying with less energy, and the other is to stimulate a manufacturer to actually produce, for sale, a solar drying bin so that farm operators who want to use one will have a place to buy it. (It should be remembered that bin-drying did not become commonplace until manufacturers offered a "package" drying bin.)

This bin has a capacity of 5000 bushels, uses a 10 hp Sukup centrifugal fan, and has a 20-kilowatt electric heater. The solar collector is corrugated steel, with a black co-polymer plastic coating, factory-

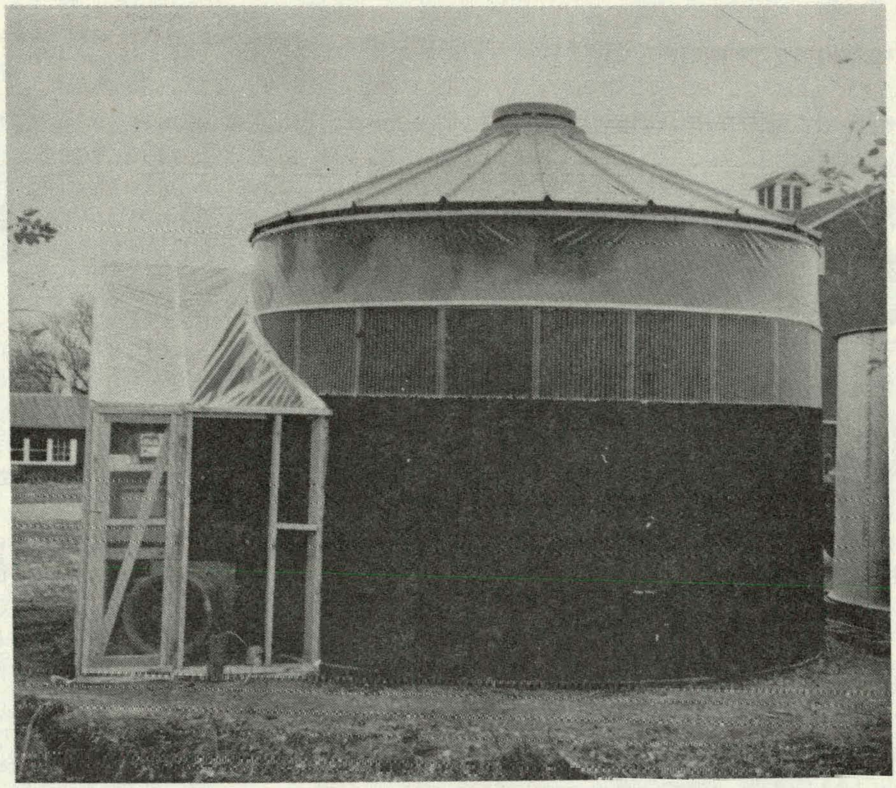

Figure 3. Redfield 5-collector solar drying bin, 1974.

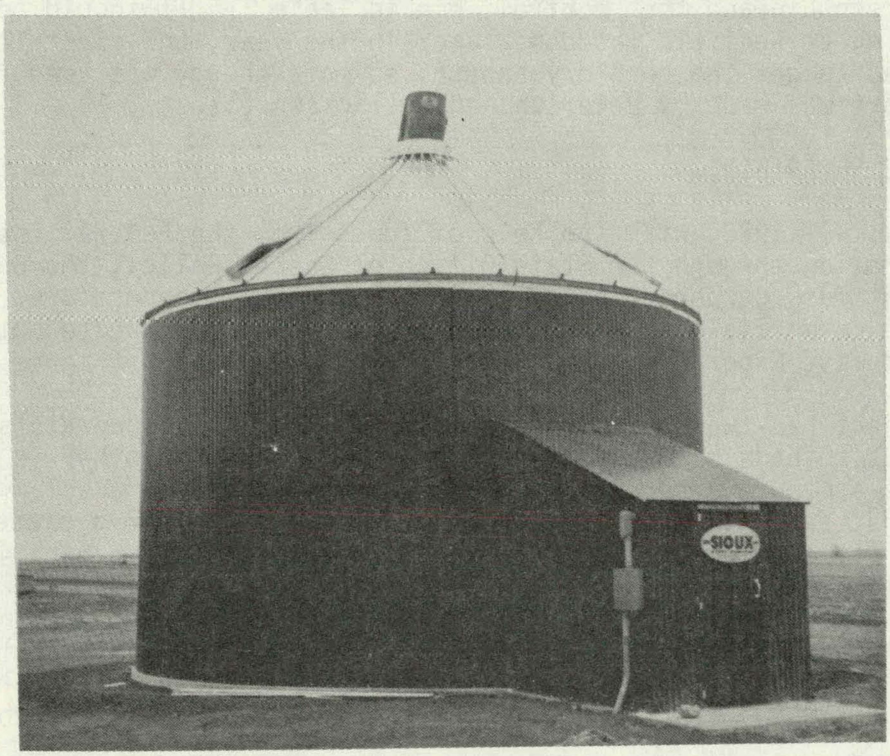

Figure 4. Manufactured prototype solar drying bin, SDSU Southeast Experiment Farm, (near Beresford, South Dakota) 1976.

Table 3. Performance of Five Types of Solar Collectors, Redfield Bin (Measured at noon, October 29, 1974, with 8 feet of shelled corn in bin)

Collector*	Temp. Rise Deg. F.	Airflow CFM	Heat Output BTU/HR	Efficiency
A-next to bin	12.1	219	2914.8	
A-next to plastic	16.1	112	1983.5	
		TOTAL	4898.3	63.9%
B-next to bin	9.0	347	3435.3	
B-next to plastic	11.5	77	974.0	
		TOTAL	4409.3	57.5%
C	8.7	530	5072	66.2%
D	9.2	572	5788	75.5%
E	8.5	725	5778	88.4%

Collector types:
A - suspended-sheet, polyethylene covered
B - suspended-sheet, corrugated clear fiberglass cover
C - bare-sheet, hand-corrugated from used press-plates
D - bare-sheet, corrugated aluminum roofing
E - bare-sheet, corrugated galvanized steel roofing. (Values for E may have been influenced by location next to plenum of warmed air. In 1975, with inside wall insulated, values were quite close to that of D.)

applied, which it is hoped will be both cheaper and more long-lived than the usual flat-black paint. This idea was advanced by the manufacturer, Sioux Steel Company of Sioux Falls, South Dakota, and reflectance testing of a sample indicated that it absorbed solar radiation as well as flat-black paint.

It was no small job to locate high-moisture corn in draught-stricken South Dakota (no corn for grain was harvested on the University farm where the bin is lcoated) but 1300 bushels was located and "borrowed" from a neighbor and dried in the solar bin.

Using no heat other than solar, the 1300 bushels were dried down from 20½ percent to 14½ percent moisture in five days of continuous fan operation, from November 17-22. Energy used was 1170 KWH, or 0.9 KWH per bushel.

With the bin one-fourth filled, the solar energy provided a 5 degree temperature rise at noon in the airstream. The 10 hp fan adds another 2 degrees. Temperature rise should be higher with a full bin, when airflow will be less. (It should be noted that as you increase the diameter of a bin, you increase bushel capacity faster than you increase collector area. Doubling the diameter would increase capacity four times while doubling the collector area. Less temperature rise is expected on larger diameter bins.) Efficiency of the solar collector was calculated at 66 percent. Pressure loss through the collector is an acceptable ½ inch of water. All solar collector parts are galvanized steel except the black coating. The bin is now commercially available, though not in quantity production, from the Sioux Steel Company, Sioux Falls, South Dakota.

I would like to mention two applications of wall-mounted solar collectors on rectangular buildings, lest I give the impression that they fit only on round structures.

A hog finishing house at the GTA research unit, near Ellis, South Dakota, has a bare-sheet collector mounted on the south wall and south-sloped roof, which is used to preheat the incoming ventilation air. Mylo Hellickson, SDSU, is project director.

A machine shed addition near Bloomington, Illinois, has 1400 square feet of fiberglass-covered solar collector mounted on the south wall and south roof slope. This is used to provide up to 7 degrees F. temperature rise on the air for two 10 kw drying fans. Coert D. Smit and Gene C. Shove directed this installation.

WHAT MAKES THEM WORK?

It is probably logical to attempt some explanation of how our results can indicate such good efficiency for bare-sheet collectors. (They are actually more efficient than the plastic-covered ones on the Redfield bin.)

First, it should be noted that with most transparent materials, something like 80 to 85 percent of the solar energy actually gets through the cover to the black sheet. With a bare-sheet, 100 percent strikes the black absorber so it has an advantage in that respect. Also, most transparent covers are somewhat glossy, and reflect more energy when sunlight strikes them at an angle, than does a flat-black surface.

Second, we have paid close attention to air velocities when designing solar collectors, generally aiming for 1000 feet per minute (1000 cfm per square foot of crossection area). The amount of heat transfer from a surface to an airstream is in direct proportion to the velocity of the airstream. Sobel and Buelow (2) show a substantial increase in efficiency with higher air velocities.

In the Redfield bin air velocities in the bare-sheet collectors were higher, and temperature rises were lower, both of which improve efficiency. It appears that the air velocity should be as high as you can allow without excessive pressure loss. A tradeoff is necessary.

I am not saying that bare-sheet collectors are "better" than those with transparent covers; just that in our area it appears that lower cost and longer life offset whatever sacrifice in efficiency exists. Where higher temperature rises are important, a more costly, shorter-lived collector may well be justified.

HOW CAN WE MAKE THEM BETTER?

There is not enough information available about low-cost air-heater solar collectors suitable for crop-drying. We should be able to predict more closely the performance of a given solar collector design, particularly with different air velocities.

We should also examine some innovative designs that we know could be fabricated readily. We need this information in order to evaluate the tradeoffs necessary between efficiency and cost.

Figure 5a illustrates the "punched-tab" solar absorber patented by Iowa State University for house heating. The tabs provide more contact with the airstream, increase turbulence, and improve efficiency. Sunlight penetrates the holes left by punching out the tabs, so the backside also becomes a solar absorber, and another surface to conduct heat to the airstream. Could a low-cost version of something similar to this be used for crop-drying, even in a bare-sheet design?

Figure 5b shows a vee-corrugated absorber with airflow parallel to the vees. This one is a "sawtooth" design, intended for vertical-wall mounting. The vees provide more area for heat transfer from the absorber to the air stream. Vees with 45 degree angles will provide

2½ times as much surface area. This may not take more actual metal; the corrugations add stiffness. The vees perform another useful function; they force sunlight to undergo at least two reflections before it can escape. No surface is a perfect absorber, and they become poorer as they age or become dusty. The extra reflections are illustrated in Figure 5c. Forcing two reflections in this way will convert a surface of 80 percent absorbance to 96 percent absorbance. This has been described by Tabor (3).

CONCLUSION

I would like to compare the solar collectors I have described with Henry Ford's Model "T" car. Hopefully, we have something that will work, and is affordable, but we do have room for many refinements.

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2. Sobel, A. T. and Fred Buelow, 1963, "Galvanized Steel Roof Construction for Solar Heating", Agricultural Engineering 44(6): 312-313.

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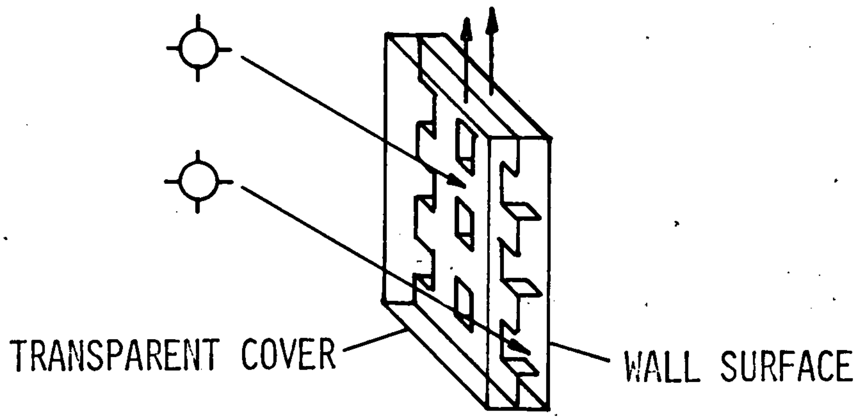
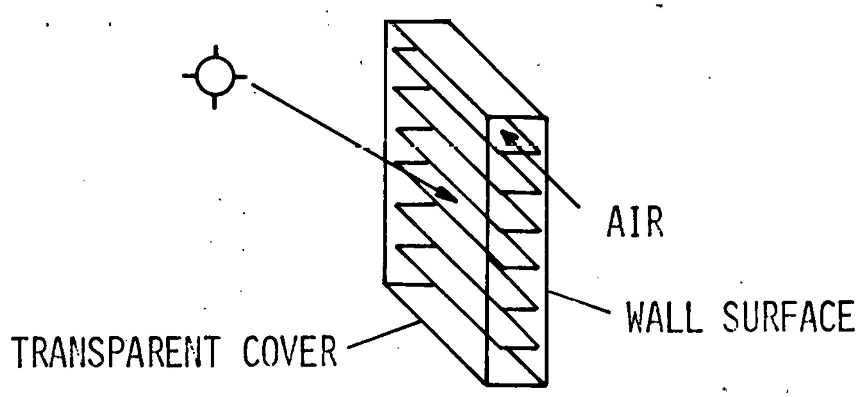
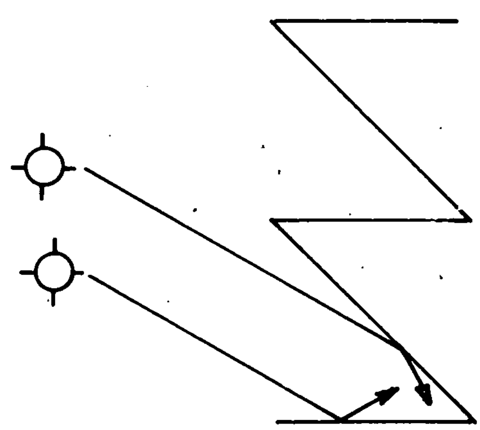


5 (A) PUNCHED-TAB ABSORBER



5 (B) VEE-CORRUGATED ABSORBER (CORRUGATIONS HORIZONTAL)



5 (C) REFLECTIONS REQUIRED FOR SOLAR RADIATION ESCAPE

FIGURE 5. SPECIAL TYPES OF SOLAR ABSORBERS

BUILDING ROOF AND WALL COLLECTORS

Marvin D. Hall[1]

The use of solar collectors as primary heat sources has been slow in developing. This slow development has been based on two reasons: (1) fuel (gas, oil and electric) has been available in most areas and is still fairly cheap; therefore, the economic advantages have been questionable, and (2) solar energy is variable; therefore, a heat storage system is needed. My approach to collecting and utilizing solar energy is to keep collecting costs low by incorporating the collector as part of the building structure and to use low temperature solar energy on farmstead applications where it can easily be adopted such as: (1) livestock ventilation systems, and (2) crop drying. Air seems to be the most practical method of transferring heat for agricultural use as air is needed for crop drying and livestock shelter ventilation systems. No, or very little effort has been made to modify standard building designs or shapes for maximum solar orientation.

BARE PLATE COLLECTORS

Building roofs and walls become bare plate collectors when provision is made to move air along the back side of galvanized steel or colored steel roofing and wall sheets (Fig.1). The important factor with this type of collector is to maintain a minimum air velocity of 500 ft/min and a maximum of less than 1500 ft/min. Pressure drop through the collector should be kept below 1/8 inch water column for livestock shelter heating and less than 1/2 inch water column for grain drying systems. When the wall or roof collector is to be used for grain drying only, it is not necessary to insulate below the collector area. The heat transfer rate is so high with the high airflow that heat loss is minimal.

COVERED PLATE COLLECTORS

Clear fiberglass is becoming popular as a cover for covered plate wall and roof collectors (Fig. 2). There are several grades of this material on the market. Fiberglass roofing panels used have been of material weighing 5 oz/sq ft with a tedlar coating on the exterior. This material usually carries a 20 year guarantee when used for greenhouses, but manufacturers are unwilling at this time to guarantee performance when used as cover plates for solar collectors. Fiberglass building roofs and walls have not been in use long enough to evaluate life and durability.

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[1]Area Agricultural Engineer, Cooperative Extension Service, Region 3, University of Illinois, Macomb, Illinois

STORAGE

Most solar grain drying and livestock shelter heating systems are operating without heat storage. However, some machine sheds that incorporate an insulated shop have used the concrete floor with a 1 to 2 ft rock bed below the floor for heat storage. This concept seems to be working very well and is low in cost to build.

SUMMARY

The utilization of low temperature solar heat seems to be a very practical and economical practice for livestock shelter ventilation and grain drying. If the collector can be incorporated in a new or existing building where it can function as a wall or roof, it puts the solar heating aspect of the system on a very sound economical base. The following precautions should be taken:

(1) Ventilate the attic or the air chamber during summer months to avoid high temperature build-ups,

(2) Use fiberglass sealer or caulking compound to seal all joints and laps,

(3) Avoid high negative or positive pressures in ducts, wall or roof cavities (1/2 inch water column for grain drying and 1/8 inch water column for livestock shelter ventilation),

(4) Insulate and seal below the air cavity on any building that is going to use the heat in that particular structure,

(5) Be sure material used for roofing and sidewalls is well nailed, i.e., if clear fiberglass is used, self drilling screws are advisable instead of nails,

(6) If steel is used as a bare plate collector use a dark color (black, green or red). Galvanized steel is also acceptable and improves with age,

(7) If clear fiberglass roofing is used, be sure the material is clear, colored fiberglass is not acceptable, and

(8) Be sure to screen all air inlets to roof and wall cavities to prevent birds and rodents from entering (1/4 inch mesh hardware cloth works very well for this purpose).

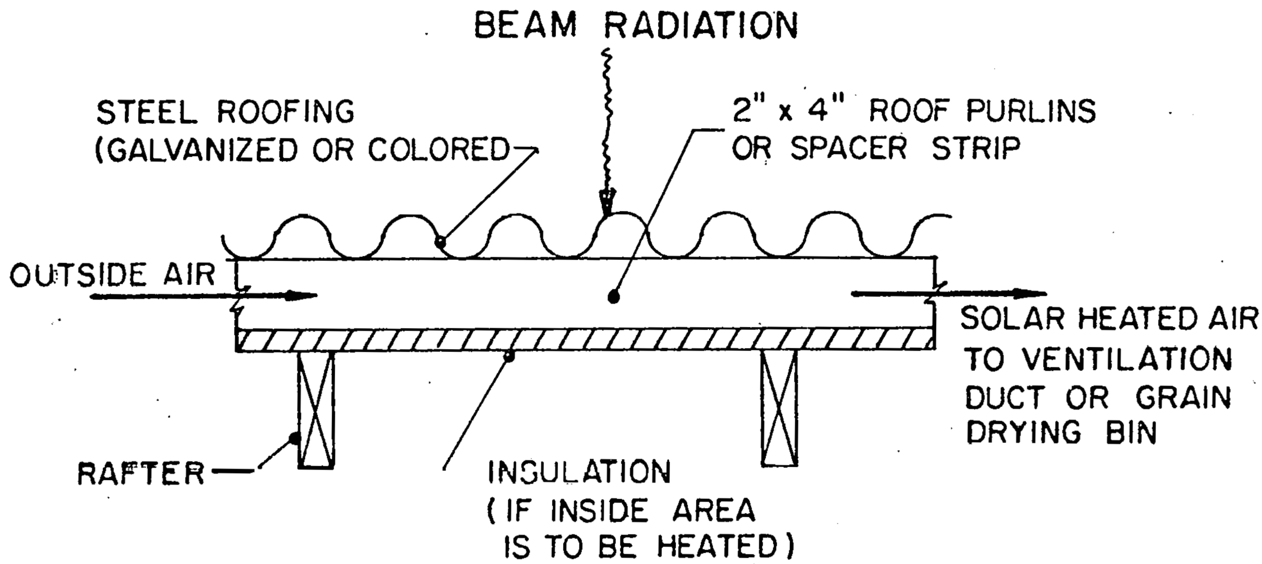

Fig. 1. Bare plate solar energy collector constructed as an integral part of a building roof.

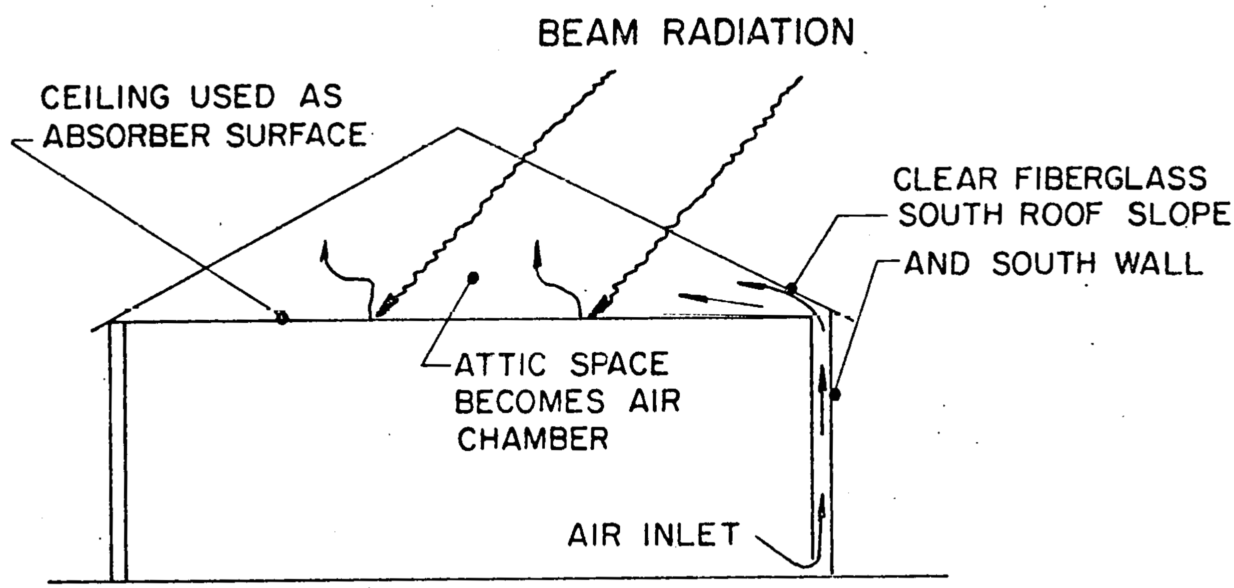

Fig. 2. Typical shape of machine sheds and livestock buildings utilizing clear fiberglass as a covered plate solar energy collector.

GRAIN STORAGE COLLECTOR COMBINATIONS

Ralph Lipper[1] and J. C. Welker[2]

The concept of using solar energy as supplemental heat for grain drying is attractive since a uniform or controlled heat supply is not essential and low air temperature increases can be tolerated. With low temperature increases, reasonable efficiencies can be obtained from relatively simple, low-cost solar collectors. At Kansas State University, we demonstrated as early as 1960 that adding a solar collector to a natural air grain drying system can reduce drying time and electric energy required for fan power. However, we concluded that the fundamental shortcomings of attempting to use solar energy simply as a direct substitute for fuel burning or electric heaters in conventional deep-bed drying systems would preclude their widespread adoption by farmers, at least in Kansas. We have learned nothing up to this time to alter that conclusion.

In Kansas, the ambient air usually has a relative humidity low enough to reduce grain to the desired moisture content any time that the sun shines. Adding heat at those times overdries grain where the air enters. Overdrying has limited potential as a form of heat storage. But our tests always resulted in overdrying of the lower grain layer with upflow air even with 24-hour fan operation. So the solar energy collected was poorly utilized on the crucial last-to-dry, top layer. Adding a solar collector to a conventional in-storage drying system to reduce grain deterioration that will take place one or two years out of ten in the upper few feet of grain in the bin is unlikely to be cost effective with any of the collectors we have known to be tested.

Addition of stirring devices could alleviate the problems of overdrying and poor utilization of solar energy. But that calls for investing another $1200 or more that must be charged against that small volume of grain which may not dry rapidly enough once or twice in a decade.

Performance of conventional natural air and low-temperature dryers in Kansas could be improved more by increasing air flow rates when the sun shines than by heating the air a few more degrees with solar energy. But the high energy cost for moving air at high velocities through deep bins is limiting. Use of shallow grain beds raises the limit on air flow rates. But shallow beds in relatively small flat storages have the disadvantages of high investment per bushel stored and high labor requirement for unloading. For those reasons, we attempted to work with a system that we thought might be developed into low cost flat storage for shallow-bed drying. The system would also present a relatively large surface area to the sun for each unit of volume stored.

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[1]Professor of Agricultural Engineering, Kansas State University, Manhattan, Kansas

[2]Research Assistant, Department of Agricultural Engineering, Kansas State University, Manhattan, Kansas

Our hope and objective as we attempted to conceptualize systems was to force ourselves, and perhaps others, out of what we regard as a dead-end approach of attaching various kinds of collectors to conventional drying systems.

THE SYSTEMS TESTED

We already owned a 30' x 40' fiberglass reinforced plastic, air-inflated structure. Solar transmittance of the white fabric was about 60%. It was rigid enough when inflated to a static pressure of one inch of water to withstand high wind velocities. In the summer of 1976 we tested it for strength up to 4 inches of static pressure. As shown in Figure 1, it had a low rectangular dome profile. The top of the dome was about 10 feet above ground level.

We used corrugated plastic drain tile with open area enlarged to 10 percent of the surface area for air ducts on the floor. The flexible ducts were spaced 2 feet apart and placed on top of a 15 mil tarpaper ground cover. Earth was mounded over the tile around the ground line of the building to provide an air seal and drainage away from the building wall. The building was erected over the ducts and the floor area was divided into 6 bins, Figure 2.

It was necessary and desirable to divide the floor area into bins rather than to leave it as one large bin, since air flow was to be downward through the grain. The space between the grain surface and building roof was the inlet air plenum. Thus, any solar radiation captured on or under the roof would warm air before it entered the grain. But, if the top layer of grain were dried to a moisture content lower than equilibrium with entering air and new, wetter grain were spread on top of it, no moisture would be removed from the system until the dried grain had been re-wet to equilibrium with saturated air. Dividing the floor area into bins made it possible, by filling one bin at a time, to avoid the re-wetting problem. In addition, it added flexibility to operation of the system.

The first grain to be harvested could be placed in one bin and the air outlets from all other bins could be closed. That would direct all the air and all the solar energy available to the one bin. Rapid initial drying in that bin would prolong the time available for completion of drying. The available drying energy could then be diverted to other bins as the harvest progressed. Any bin that was dry enough to warrant delay in further drying could be put on "hold" by throttling the air outlets while drying capacity was directed to that grain most in need of rapid initial moisture reduction.

A sleeve through the plastic dome above each bin provided means for inserting an auger for emptying. Manual moving of grain to the auger inlet was reduced by the flexible nature of the sleeve and bin roof. That permitted limited maneuvering of the auger inlet position.

The idea for another kind of plastic fabric storage was derived from a 1000-bushel reinforced kraft paper grain storage bag that was being marketed by a regional farm cooperative at a close-out price less than $100, see Figure 3. We had a similar bag built from 24-mil, laminated, dark green plastic with a tensil strength of 700 pounds per inch of width and added a clear plastic dome top, Figure 1. A clear fiberglass reinforced plastic collector cover was sewed to the bin wall to make a solar collector out of two-thirds of the bin wall area. Air from the fan was delivered to the space between the bin wall and the clear collector cover, then through holes in the upper bin wall into the volume between the grain surface and the dome. Static pressure for moving air downward through the grain provided pressure to support the dome. Corrugated plastic drain tile with the enlarged openings protruded through sleeves in the bin wall at ground level. They were laid in a radial pattern on the plastic bin floor for air exhaust ducts. The "bag" was 15 feet in diameter with 6-foot side walls. The structure was centered over a cone shaped pit in the earth that was 2.5 feet deep and 3.5 feet in diameter. A larger pit would have allowed more grain to flow to the center by gravity during emptying, but we wanted to test the concept that, by closing off the exhaust ducts, enough lift could be provided by static pressure under the dome to lift and deform the side walls enough to move grain off the annular ring between the pit and side wall.

Since air flow was downward and re-wetting of grain could be a problem, if filling was resumed after a period of drying, size of the bag was limited by the amount of grain that might be harvested in one of two days. Structural considerations also limited size of the bag.

RESULTS

The 30' x 40' flat storage was erected in late summer on a site provided by the Morrison Grain Company at Salina, Kansas. We had an agreement with Morrison's to supply grain for tests and its subsidiary, Thermo-Flex Inc., to fabricate and modify the plastic structures. Thermo-Flex has built many air-inflated and other types of plastic structures, shelters, and grain covers.

Loading part of the structure to the design depth of 4 feet with dry grain showed that the side walls would hold their shape against the grain pressure as long as the static pressure inside the building was maintained. However, when pressure inside the building was reduced by people moving through the personnel entry slot, the walls slumped outward. We erected 2-foot high plywood sidewalls outside the building to support grain pressure against the lower wall. The building had a plastic flap 2 feet wide at the ground line that lay on the ground inside the building for an air seal. Difficulty was encountered in achieving a good air seal where the flap rode over the air ducts. That problem could be alleviated by simple design changes.

Previous experience over several months had shown that, with all air outlets sealed, a one-quarter horsepower centrifugal fan would provide for air leakage and maintain adequate static pressure inside the structure. But, we made a modification that ultimately caused failure of the buildings. The personnel entry slot was covered by a hanging flap and held against the slot by pressure inside the building. We moved it from ground level to a position above the nearly vertical portion of the end wall, so we could enter above the grain surface. The result was failure to self-close after periods of reduced inside pressure. Each of several brief power failures caused the building to collapse. With no responsible person in the immediate vicinity, high winds tore the unsupported structure beyond repair.

We did not place wet grain in the structure for drying before it failed. We have no doubt that, except for our mistakes, the system would have performed satisfactorily as a drier. We feel that some form of the overall concept might have utility where there is frequent need for temporary storage. The building itself, if it were to be placed over a permanent slab with ducts and ground anchors already in place, would take two men less than two hours to erect. Buildings of the type we used can be supplied for about $1.50 per square foot of area covered.

We dried 850 bushels of sorghum grain from to 18.6 w.b. in the bag with plastic dome. The grain holding bag itself performed well. The reinforced clear plastic collector cover on the side wall became torn at stress points along the sewed seams under static pressures as high as 4.0 inches. The round plastic drain tile used for air ducts took an oblong shape under the weight of 6 feet of grain, but we could detect no impairment of its function. The dome did not provide enough lift to move grain into the shallow auger pit. The cost, exclusive of fan and motor, was about $1050. Our conclusion is that the cost is likely to be too high for temporary storage and the need to keep it inflated even with a low horsepower fan, plus its vulnerability to damage, precludes its use for long term storage.

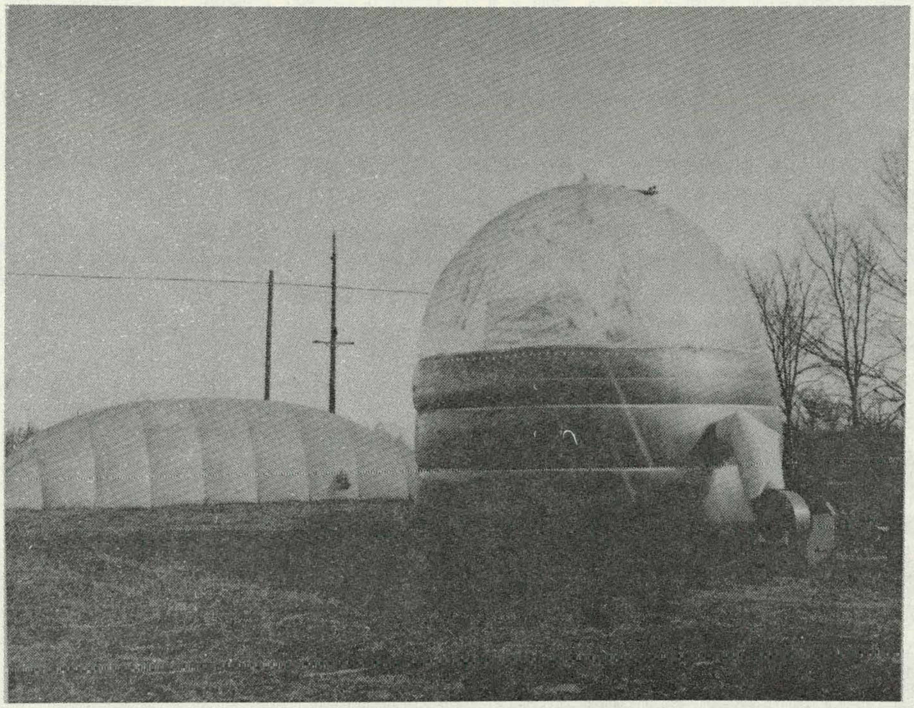

Figure 1. Solar grain drying bag with plastic drain tile used for ducts in foreground. Flat-storage-collector background.

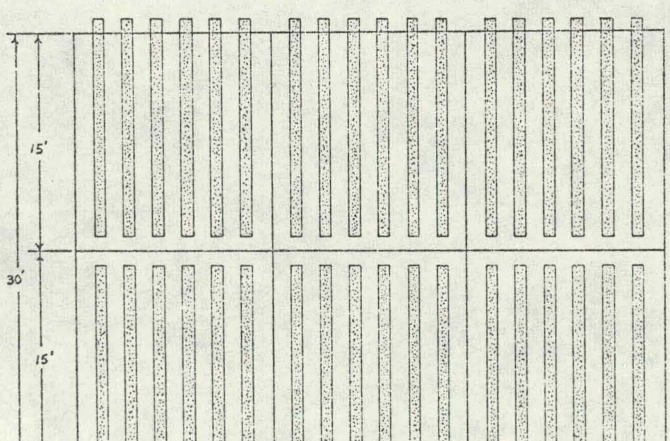

Figure 2. Floor plan of flat-storage-collector.

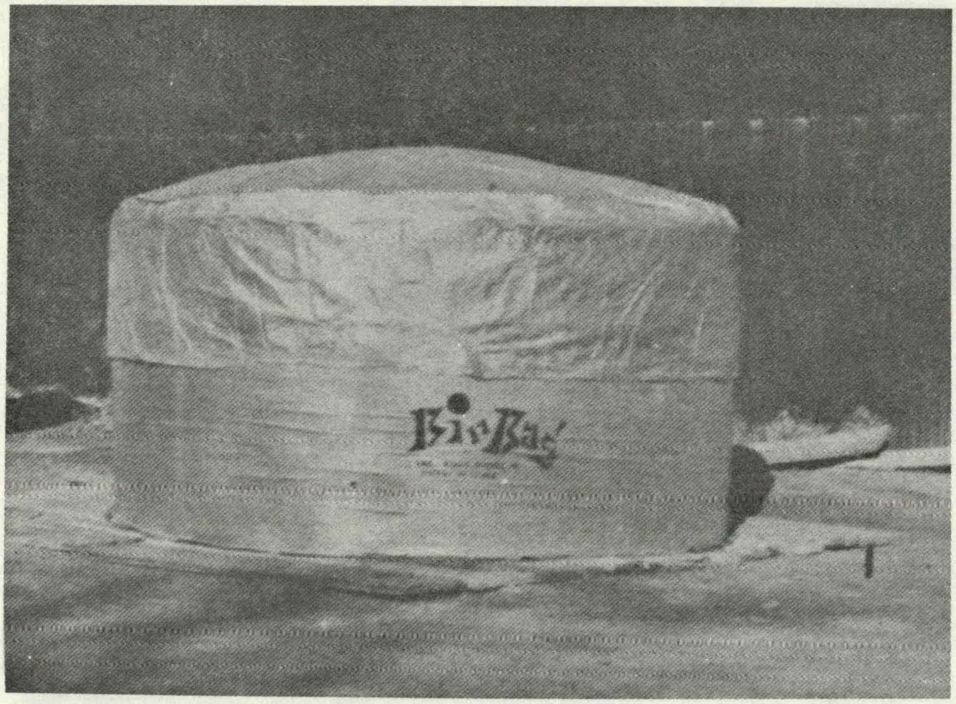

Figure 3. Kraft paper bag used for 1000-bushel grain storage.

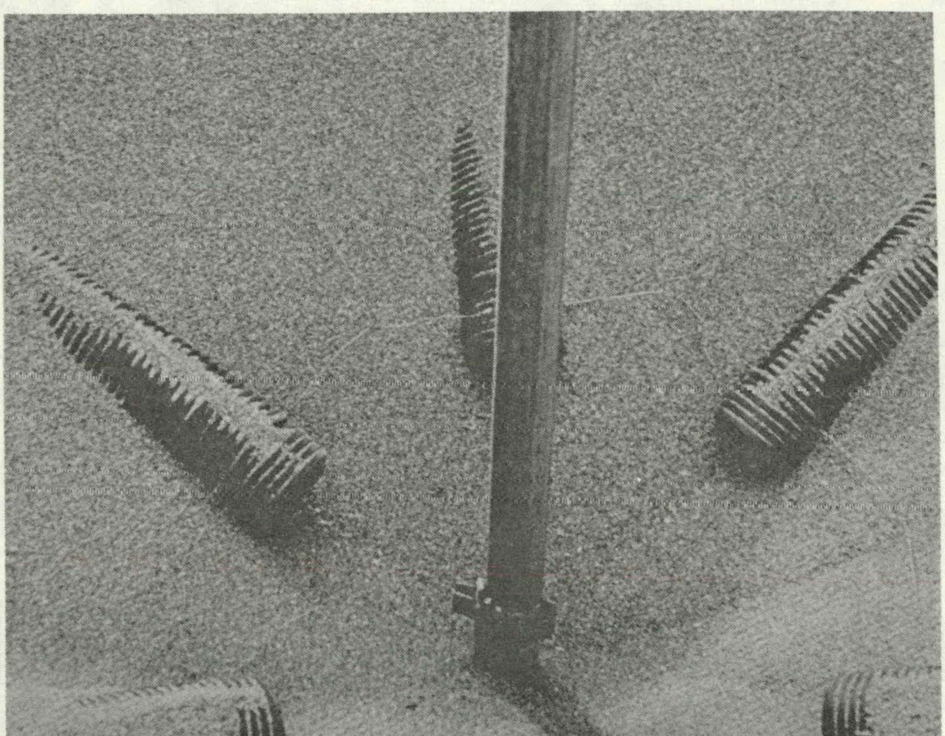

Figure 4. Inside of grain bag during unloading with vertical auger showing 5 of the 12 radial air ducts.

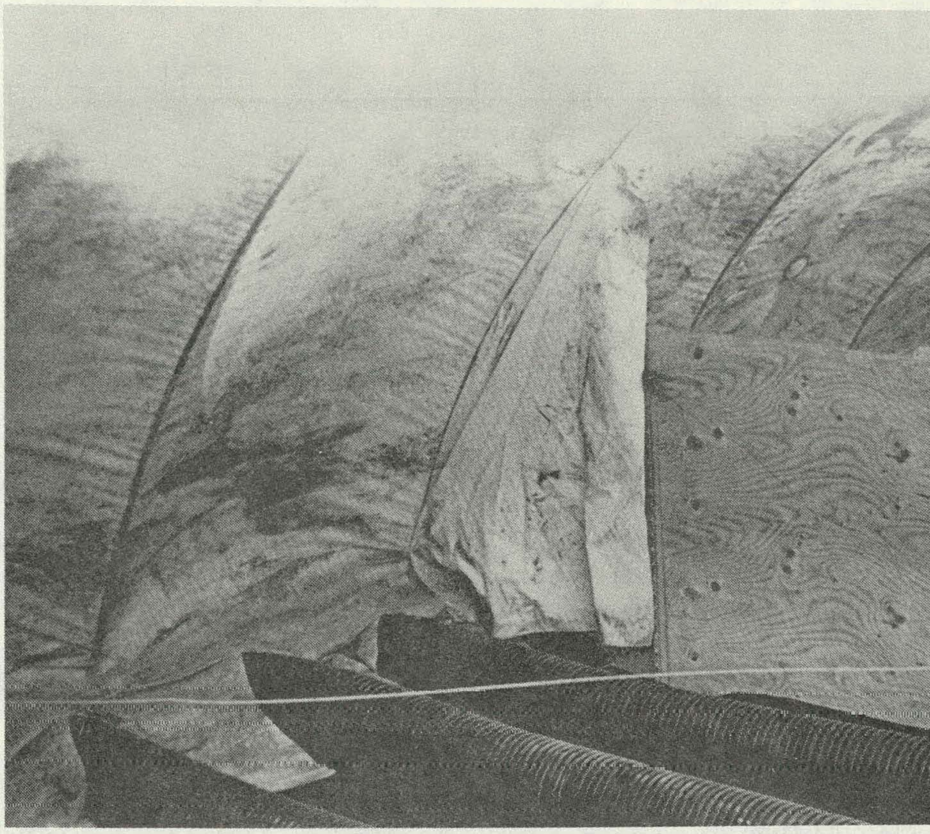

Figure 5. Inside of flat storage showing air ducts and one bin partition.

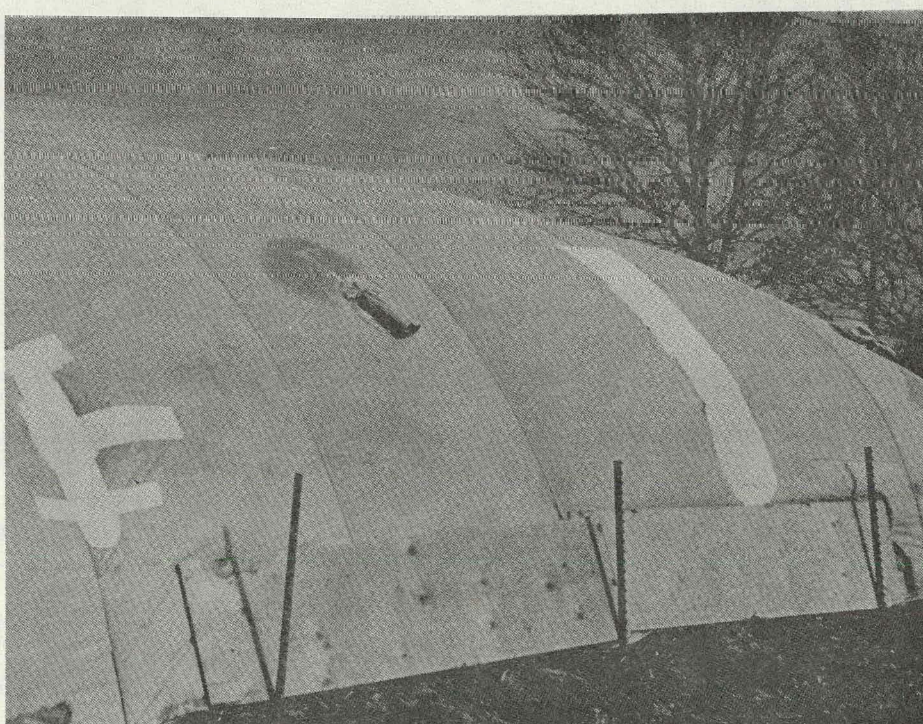

Figure 6. Outside of flat storage showing air ducts and plywood wall support.

FOCUSING SOLAR ENERGY COLLECTORS-SUN TRACKING TYPE

B. F. Parker, O. J. Loewer, Jr., and G. M. White[1]

INTRODUCTION

In the Southeast, grain drying without risk of spoilage requires a faster rate of drying than in the Midwest due to higher ambient temperatures during the harvest season. Therefore, the Southeast can not depend upon low temperature drying methods such as those in the upper Midwest. The focusing solar collector is unique in that it can collect solar energy at temperatures of 250F or more; thus, it is technically possible to use solar energy to heat air for high temperature grain drying.

A simple examination of sun-tracking types of focusing collectors shows that with reasonable size units the energy collected during the grain harvesting season is insufficient for drying large quantities of grain. Therefore, it is essential to provide a heat storage unit. Heating the storage medium to a relatively high temperature will significantly reduce the quantity of storage volume required to store a given quantity of heat.

FOCUSING COLLECTORS

The tracking type focusing collector has several stringent requirements for efficient operation:

1. A rotation mechanism and control for continuous adjustment to follow the sun
2. An accurate surface for focusing the rays of the sun
3. A high refectivity or high transmissivity of the focusing system
4. High absorptivity and low heat loss from the high temperature solar energy absorber.

Two years ago each of these problems seemed to be of major importance. Since that time, however, very significant advances have been made in several areas. For example, control systems (including sensing devices) for continuously aiming of a collector toward the sun are now on the market for approximately $150. Several manufacturers are marketing focusing collectors systems including accurate surfaces. The reflectivity of focusing surfaces have been improved from approximately 70% to 85% and one company has successfully vacuum deposited silver on a teflon film to provide a reflectivity of 95%. These significant advances are encouraging.

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[1]Professor, Assistant Extension Professor, and Associate Professor, Agricultural Engineering Department, University of Kentucky, Lexington, Kentucky

MANUFACTURERS OF FOCUSING COLLECTORS - TRACKING TYPES

Several of the manufacturers of focusing collectors are as follows*:

Sunpower Systems, Tempe, Arizona
Hexcel Corporation, Scottsdale, Arizona
Northrup Inc., Hutchins, Texas
Albuquerque Western Industry, Albuquerque, New Mexico
Solar Tek, San Diego, California
Scientific-Atlanta, Inc., Atlanta, Georgia
Better Builders Association, Bonsall, California
Brown Manufacturing Company, Oklahoma City, Oklahoma
Mel Kiser and Associates, Tucson, Arizona
Nordam, Tusla, Oklahoma

The Northrup collector utilizes a fresnel lens to focus solar radiation onto a line. Each collector is approximately one foot wide and 10 feet long. A liquid is circulated through a pipe to absorb the energy. These units complete with tracking presently sell for $32.00 per square foot.

Hexcel, Supower, Solar Tek and Albuquerque Industries manufacture a cylindrical parabola for reflecting the solar radiation onto a pipe. The most interesting development in these collectors has been the drastic reduction in prices. Solar Tek and Sunpower offer a thousand square foot system for $12.00 per square foot within their state. This is about the same cost as a high quality flat plate collector.

COLLECTOR-STORAGE CONCEPT FOR GRAIN DRYING

The focusing collector-storage concept for grain drying is based on the premise that solar energy can be collected over a period of several months, say during August and September and stored in heat storage compartments until needed for drying grains. Each compartment should be of sufficient size to store enough energy to dry the grain harvested in one day. The heat discharged from each compartment should initially be approximately 250F dropping to near 100F by the end of the drying period.

The two most common storage media are water and rock, the rock being either crushed or river gravel. Since it is desired to heat the medium above 250F, the use of water would require a pressure vessel for storage. The cost of such a storage vessel on a large scale was determined to be prohibitive; therefore, only crushed rock storage is considered in this paper.

Assuming a rock bed of approximately 1,000 cubic yards it is estimated that 1,300 to 1,600 square feet of focusing solar collector area would be required to charge it over a 60 day period. If the rock were heated to

*This list of manufacturers is not inclusive and does not imply endorsement of the collectors by the authors.

250F and then cooled down to 100F, 6.4 bushels of grain could be dried from 25% to 15.5% moisture per cubic yard of stone with a conventional high temperature drying system. That is, 6,400 bushels of grain could be dried with the energy stored in the 1,000 cubic yard rock storage. However, if it were suitable to remove only one half of the water at high temperature and to use low temperature drying for the remaining water, then the quantity of grain that could be dried would double.

FARMSTEAD ENERGY SYSTEM

It is noted that even with a large crushed rock storage, relatively modest quantities of grain can be dried with such a system. Use for grain drying could be justified only for very high fuel cost. Economics will probably demand that the collector-storage system at the farmstead be utilized at other times of the year for heating and cooling the residence, greenhouses, animal shelters and the farm shop. For farmsteads which have large energy demands in these buildings, much larger rock beds might be constructed. It should be noted that the larger the rock bed, the less heat loss per unit of heat stored, this being a significant advantage of large storage units.

COLLECTOR DEVELOPMENT AT THE UNIVERSITY OF KENTUCKY

Agricultural Engineers at the University of Kentucky have developed a unique design for a solar absorber which is particularly suitable to heating air to high temperatures. This unit employs one or two concentric glass pipes on the focal line of a cylinderical parabolic reflector with 20 to 30 longitudinal thin aluminum fins located in the smaller glass pipe. These fins serve to concentrate the solar energy focused on the glass pipe and to absorb it as well as serve as heat transfer surfaces for heating the air. One design has a collector aperature of approximately 42 sq ft with 77 sq ft of aluminum fin area to serve as heat transfer surface within a 4 inch glass pipe. This large surface area is particularly important in view of the fact that heat transmission coefficients from surfaces to air are very low compared to the coefficients for transferring heat from surfaces to a liquid. Although water might be used in this collector air has been employed since the heat can be directly stored without resorting to a pressure vessel.

SUMMARY

The technology of focusing collectors has advanced rapidly during the past two years. It appears that focusing collectors can now be manufactured to track the sun at approximately the cost of the high quality flat plate collectors. It is expected that more maintenance would be required to maintain the reflectivity of the focusing surfaces as well as the mechanical system for tracking the sun. However, the size of the storage unit to store a given quantity of energy can be reduced by using high temperatures, and the high temperatures have the potential ability to operate an absorption air conditioning system as well as to dry grain and heat buildings.

Drying grain safely in the southeast requires rapid moisture removal using relatively high temperature drying systems. Several problems must be overcome before high temperature solar drying will become practical. Development of efficient systems for storing heat energy, as well as continued collector development, need immediate attention.

NON-TRACKING SOLAR CONCENTRATORS

Mylo A. Hellickson[1]

INTRODUCTION

Solar concentrators provide one option for collection of solar energy for agricultural drying and space heating applications. A solar concentrator is a device that focuses or reflects energy from a relatively large area onto a relatively small area. Solar concentrators are particularly adaptable to situations requiring higher temperature rises and in circumstances where collector or absorber cost is high in comparison to reflector cost. Heat loss from solar systems is roughly proportional to surface area and therefore is inversely related to concentration ratio (aperture area divided by absorber area). Consequently, higher concentrations serve as one means of increasing overall system efficiency.

Historically, applications of solar energy for agricultural drying and heating applications have involved low-cost, low-temperature rise systems that are often integrated into existing farmstead structures. Certainly these systems offer potential for energy savings, but it is important that a variety of alternate systems, including solar concentrators be investigated. These investigations should not only be involved with the potential, efficiency and performance of the solar systems, but also should include consideration of the drying or heating processes.

For instance, it is possible that new drying techniques can be developed that better match the physiology of the product and its requirements for storage with the diffuse nature of the solar energy being used in the drying operation. Basically, it is important to remember that many current drying techniques have been developed for heating systems using a fuel of high energy density. Therefore, agricultural applications of solar energy would appear to take the shape of a "double-edged sword," involving both agricultural and energy implications.

It is the purpose of this paper to present information on solar concentrators. This material will be restricted to non-tracking solar concentrators so as to better integrate with other material included in these proceedings. The primary advantage associated with non-tracking solar concentrators is the simplicity obtained in comparison to tracking solar concentrators. The main disadvantage is the reduction in concentration ratio that can be achieved. Tabor (11) concluded

[1] Associate Professor, Agricultural Engineering Department, South Dakota State University, Brookings, South Dakota

that the maximum possible concentration that could be achieved with a stationary collector was approximately three. This value was accepted by the solar energy community until 1974 when Winston (13) reported on the ideal or Winston concentrator that could achieve a concentration ratio of about ten without diurnal tracking. It is worth noting that the Winston concentrator is identical in shape to the individual eye-cups of the horse-shoe crab and that the French philosopher and mathematicion Descartes had prepared identically shaped drawings in the early 1600's. This type of concentrator and others, including one being tested by the Department of Agricultural Engineering, South Dakota State University, will be discussed in the following section.

TRACKING SOLAR CONCENTRATORS

Relationships between solar elevation, acceptance angle (the angular range over which radiation is accepted without moving the collector) days from solstice and hours of solar energy are presented in Figure 1. The dotted line indicates that a stationary solar concentrator would collect energy for at least seven hours on all days of the year. However, the concentration ratio associated with this acceptance angle is quite low. This problem can be at least partially resolved by periodic adjustment of the solar concentrator. This concept seems to fit well with agricultural requirements since it can be a relatively simple procedure and the personnel required for performing this task are normally available.

The ideal or Winston concentrator, Winston (13), is illustrated in Figure 2. The term ideal does not imply that it is the ultimate in solar conentrator and is used to indicate that all of the solar rays entering the concentrator are received at the absorber. This type of concentrator actually acts as a radiation funnel. Although high concentration ratios are achieved with the Winston concentrator, a large reflector area is required, Rabl (5), and the acceptance angle is relatively limited. Typically, low acceptance angles are associated with high concentration ratios.

Rabl (5) presented several variations of the ideal concentrator (Figure 3). Normal operation of the ideal concentrator would require adjustment about every 3 or 4 days.

The stationary "sea shell" concentrator, Rabl (6), is an adaptation of the ideal concentrator, Figure 4. One advantage of this system, as illustrated, is that the output varies with season as do many heating and cooling loads. The sea shell concentrator consists of a single pasolola with one axis parallel to one of the extreme rays and a focus at the absorber. Figure 4 illustrates such a concentrator with $\pm 36°$ acceptance angles, which allow a 7-hour collection time on all days. The concentration ratio is 1.7 with normal incidence, but varies from zero to 3.4. Temperatures of up to 100°C can be achieved with selective absorber surfaces.

A stationary reflector tracking absorber (SRTA) solar collector system was presented by Steward and Kreith (9), Figure 5. This consists of a segment of a spherical mirror that remains stationary and a linear tracking absorber that rotates about a vertical axis. Although relatively simple in design and principle it does allow for high concentration ratios.

Nelson, Evans and Bansal (4) reported a weighted concentration ratio, the product of collection efficiency and geometric area ratio, of five and a collection efficiency, the ratio of the irradiance at the absorber to irradiance at the first concentrator surface, of 52% using a linear, non-tracking Fresnel lens. The concentrator, Figure 6, was oriented east-west and performed equally well for the alternate focus positions shown.

The flat plate collector is one of the most common types of solar collectors. The output of flat plate solar collectors can be increased by using mirrors along the top and/or bottom of the collectors as is shown in Figure 7. This then becomes an enhanced flat plate collector and is often referred to as the Shuman system, Tabor (11), when the collector has an east-west orientation. The mirror effect is $1 + R\frac{X}{C}$, where R is the mirror reflectivity, X is the effective mirror width and C is the collector width, Figure 7. Normally this system has hinged mirrors and requires a tilt adjustment approximately on a weekly basis. One of the major problems with this system is the peaky nature of the output. That is, high output around noon and low output in the early morning and late afternoon. This problem can be reduced by using a noon-reversing mirror system, Tabor (11), as illustrated for the east-west oriented collector in Figure 8. Major disadvantages of this system include the need to move the mirror from the west to the east end of the collector at noon and the difficulty in lining the collectors up end-to-end.

Souka and Safwat (8) presented a procedure for determining the optimum angle of tilt for mirrors on collectors and Tabor (10) discussed the relationships between the EWV (East-West Vertical), season and time and the influence of acceptance angle on stationary mirror systems. McDaniels, et al. (3) published information on energy collection versus reflector and collector orientations, latitude and sun hour away from noon for mirror enhanced flat plate collector systems. Seitel (7) reported that reflectors for flat plate absorbers are a particularly attractive alternative when the collector is restrained to an unfavorable orientation.

The use of an inflated cylinder focussing collector was reported by Tabor and Zeimer (12), and this concept was later used by Hataria and Horsefield (1) in studies conducted in California. Figure 9 provides end views of cylinders that have been constructed with transparent and a reflector sections. Detailed studies by Tabor and Ziemer (12) indicated the collector should have a triangular configuration and also indicated an improved performance if side mirrors are added. These studies also indicated that a concentration ratio of about three could be achieved with seasonal adjustments in collector orientation. One of the major advantages of this system is that the unit is easily moved to alternate locations.

The addition of "solar wings" to the wrap around solar collectors studied on several conventional drying bins, Figure 10, provides another means of increasing window area and temperature rise. It is possible to reduce cost per unit of effective collector area using this technique, but space limitations in the storage area may be a critical factor.

SDSU SOLAR ENERGY-INTENSIFIER

A solar energy-intensifier system for crop drying and agricultural space heating applications is being studied at the South Dakota State University, Agricultural Engineering Department. Cross-sectional and top views of this system are provided in Figures 11 and 12. The solar collector consists of an east-west oriented, blackened, corrugated absorber with two transparent covers on both the north and south sides. Air flows, 1000 cfm, over the collector along its entire 24-foot length with air entering along the lower south side of the 4-foot high collector. A 12-foot high, 36-foot long reflector is located north of the collector and reflects incident rays onto the north side of the collector. The reflector is parabolic in shape, is hinged at the bottom to allow for periodic, tilt adjustment and was constructed with a steel frame and masonite covered with an adhesive backed aluminum with a reflectivity of about 0.85. The reflector was made longer than the collector to allow full use of the absorber surface without diurnal tracking. A horizontal or nearly horizontal reflector near the ground on the south side of the collector is to be added to increase the concentration ratio to approximately five. Future plans include modification of this system by the addition of a recirculating air plenum and a thermal energy storage for use in agricultural space heating applications.

Several types of solar concentrators have been presented and limited performance characteristics have been discussed. In reviewing solar concentrator research it is important to remember that most studies have involved use of solar concentrators for high temperature applications. The requirements of high temperature have increased the complexity of many of these systems. For agricultural applications, where personnel are available to periodically adjust focus, greater simplicity is possible. Therefore, increased research on application of solar concentrators to agricultural applications is encouraged.

The following general concentrator characteristics were suggested by Winston (13) as being of primary importance in the evaluation of solar concentrator system performance: 1. Concentration Ratio, 2. Acceptance Angle, 3. Sensitivity to Mirror Errors, 4. Average Number of Reflections and 5. Size of Reflector Area. Aid in evaluation of solar concentrator design may also be obtained from a publication by Löf and Duffie (2). This manuscript includes a series of graphical relationships that establish reflector area ratios for maximum heat delivery for parabolic concentrators. These relationships are based on incident radiation intensity, optical properties and thermal loss rate.

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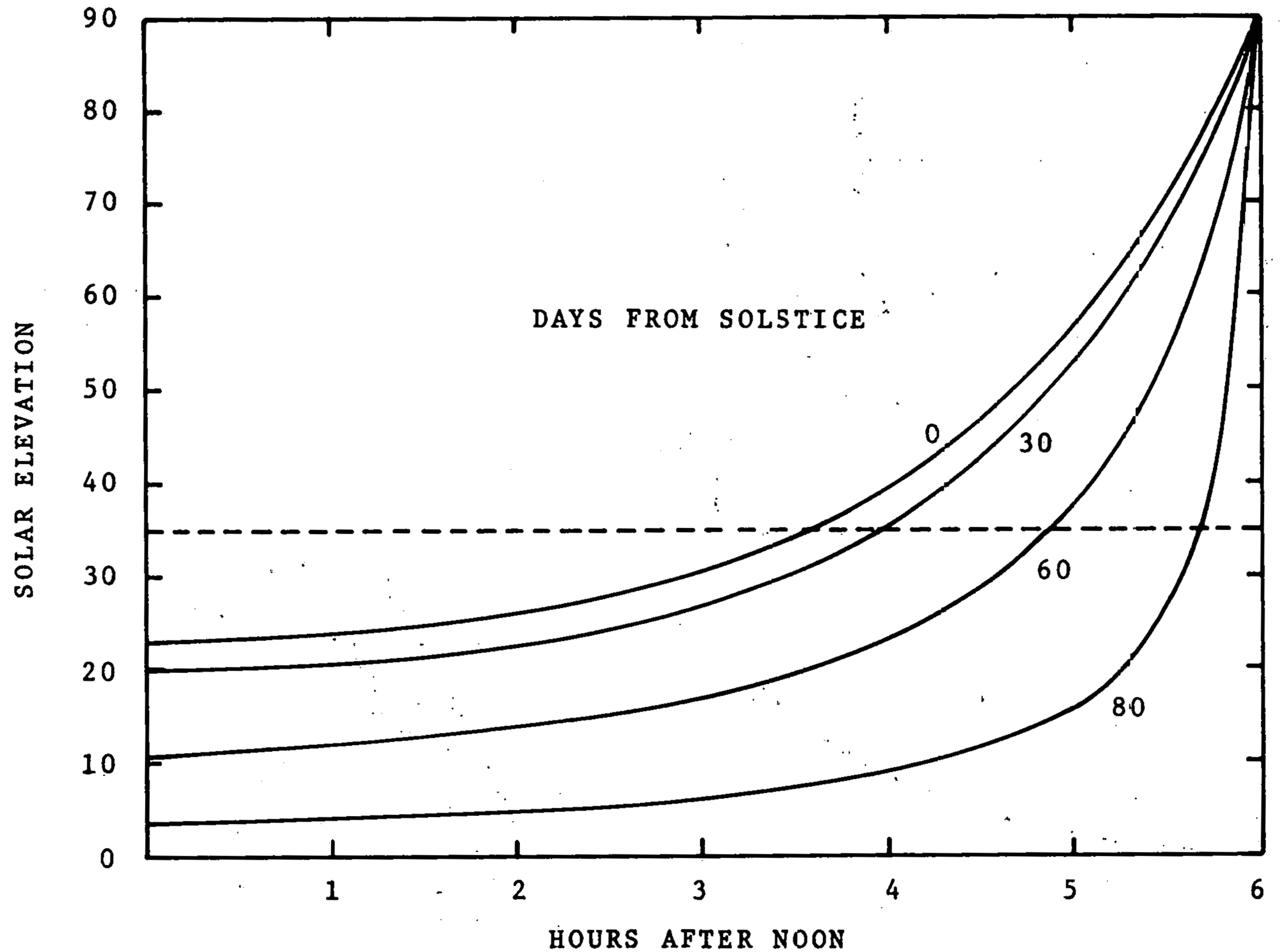


Figure 1. Relationship Between Solar Elevation and Days from Solstice on Hours of Collection Time for a Stationary Solar Collector.

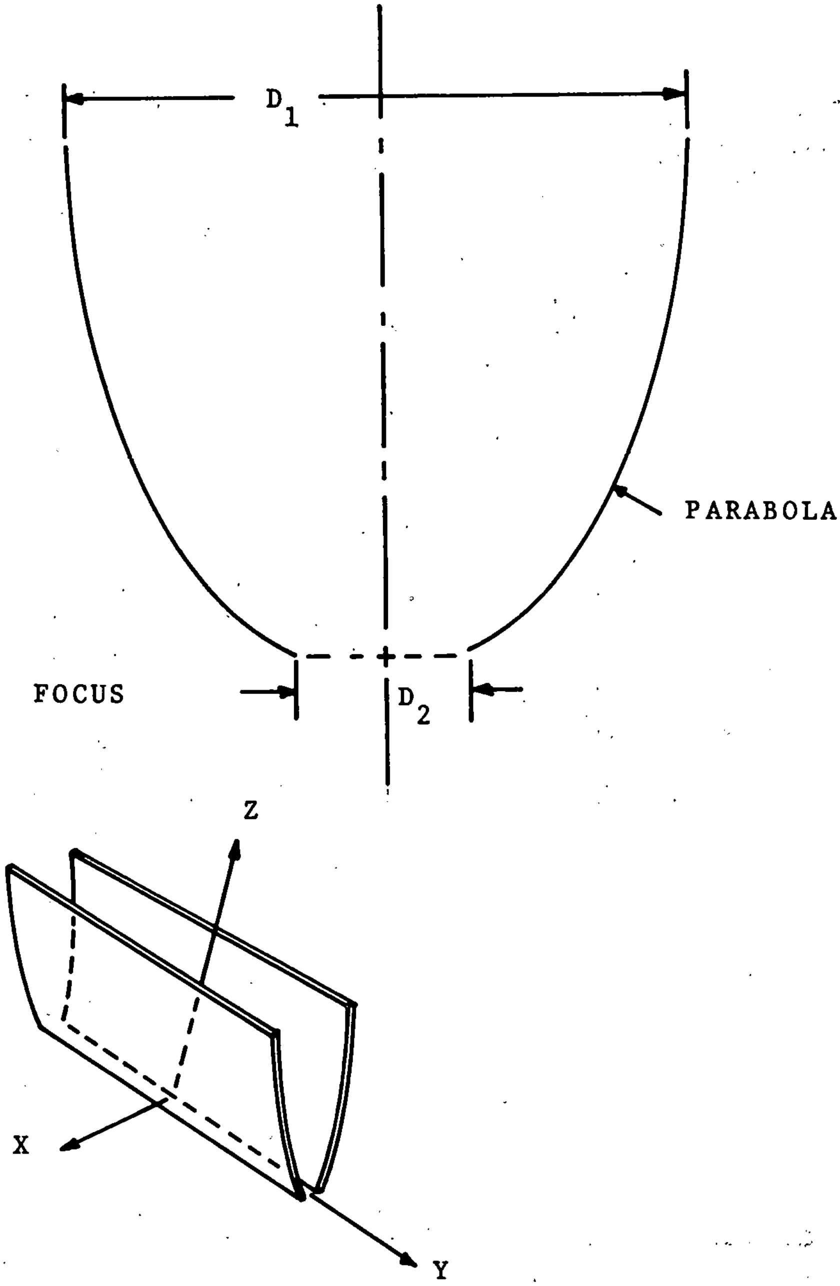


Figure 2. The Ideal or Winston Concentrator.

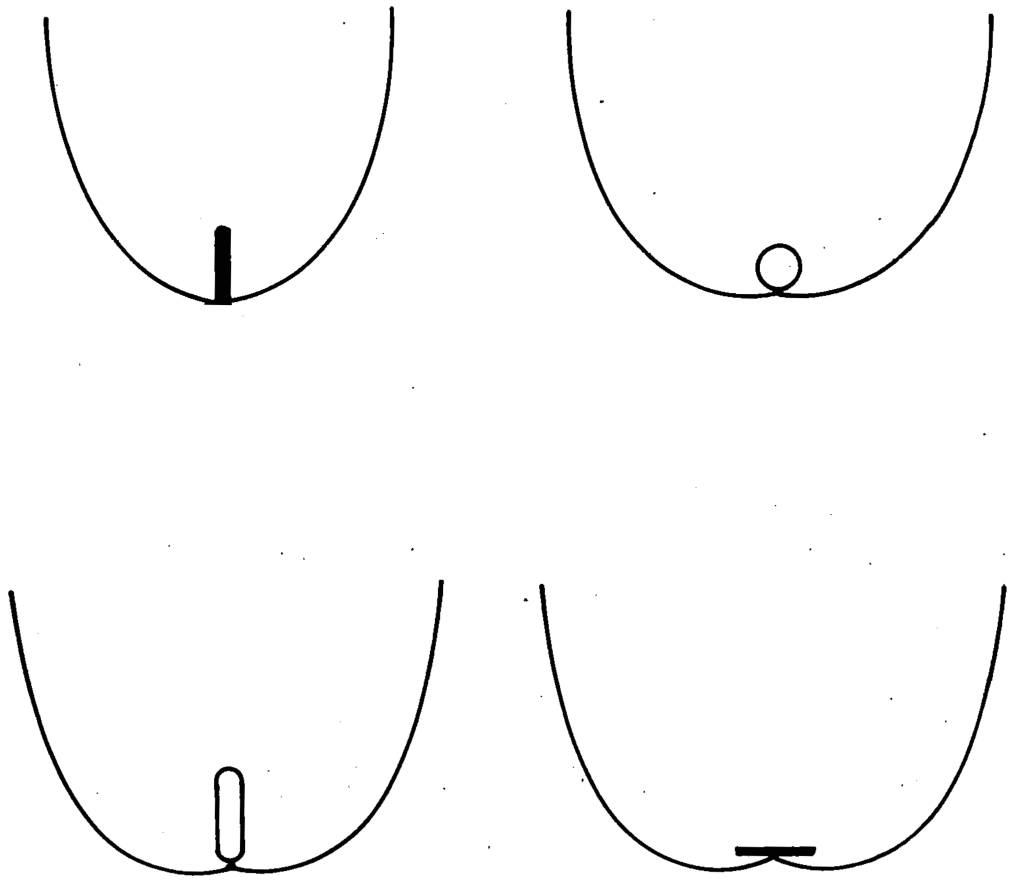


Figure 3. Variations of the Ideal Concentrator.

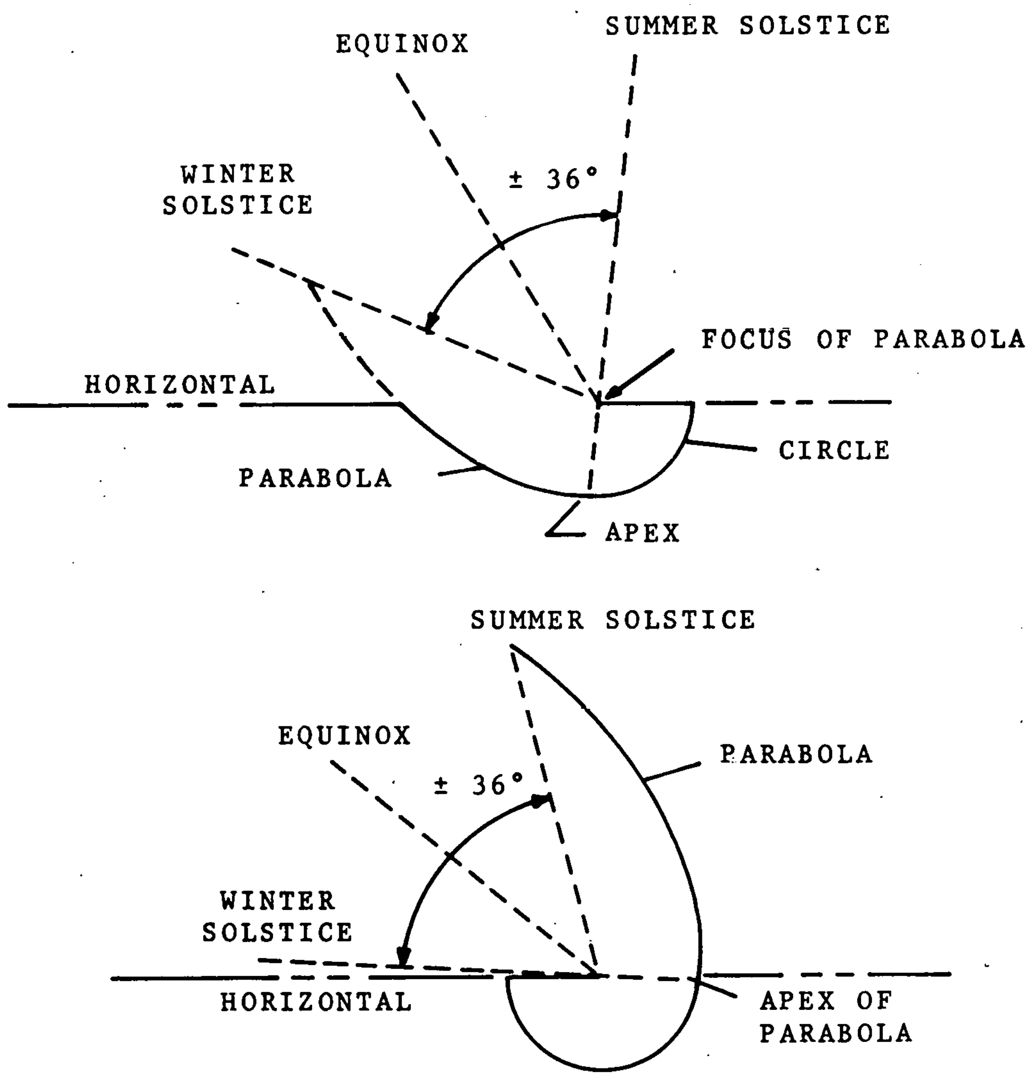


Figure 4. Sationary "Sea-Shell" Collector.

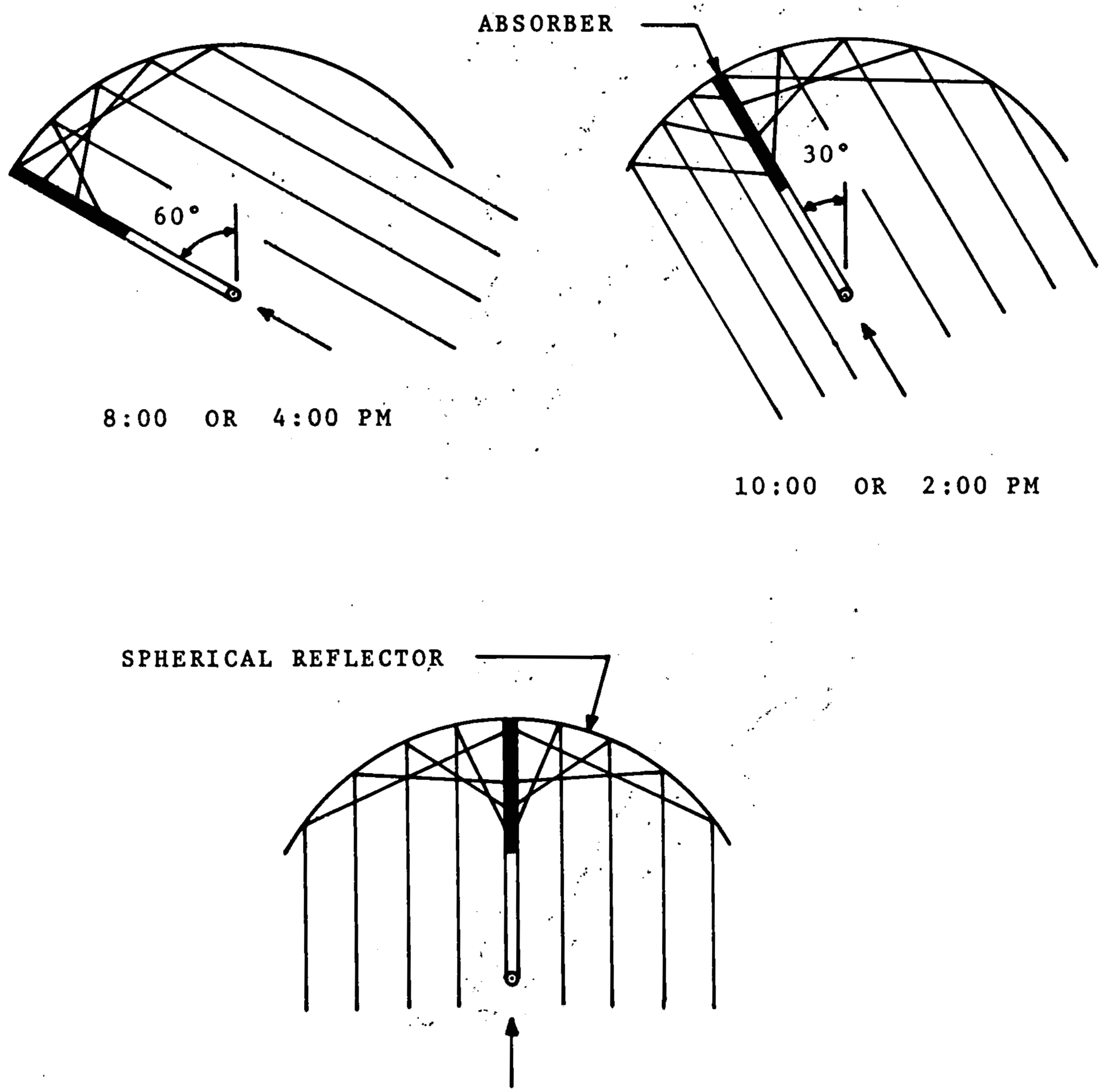
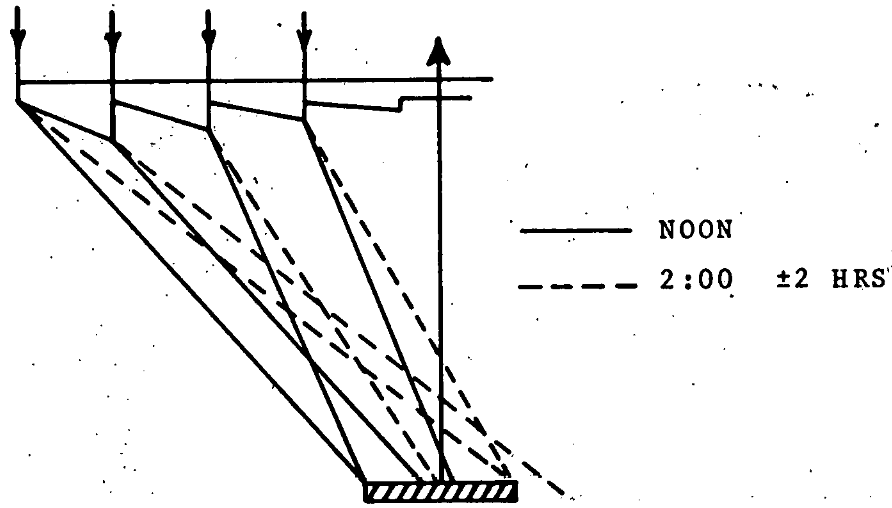


Figure 5. Stationary Reflector Tracking Absorber (SRTA) Solar Concentrator.

A



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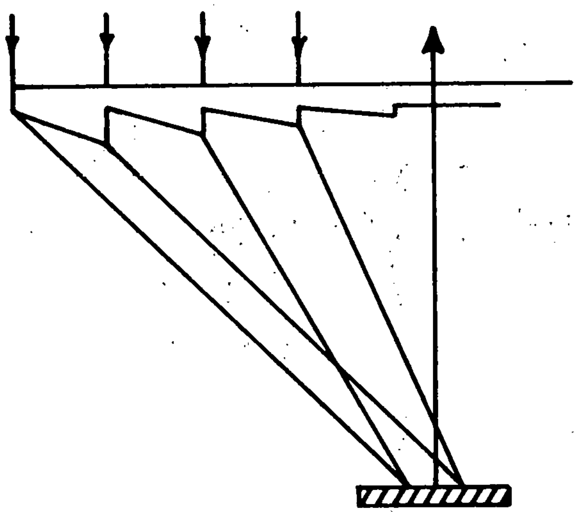


Figure 6. Linear Fresnel Lens Solar Concentrator.

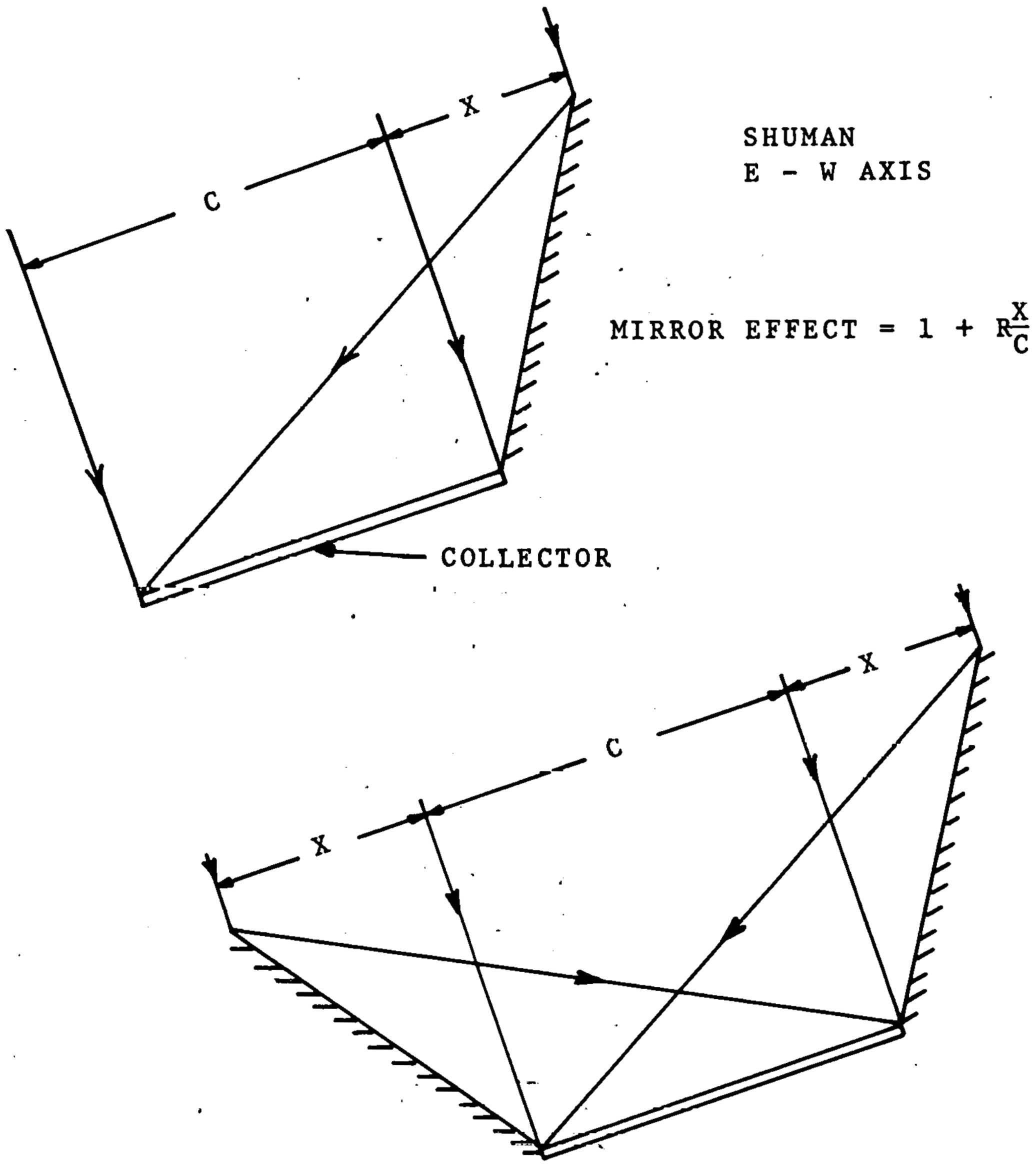


Figure 7. Mirror Enhanced Flat-Plate Collector.

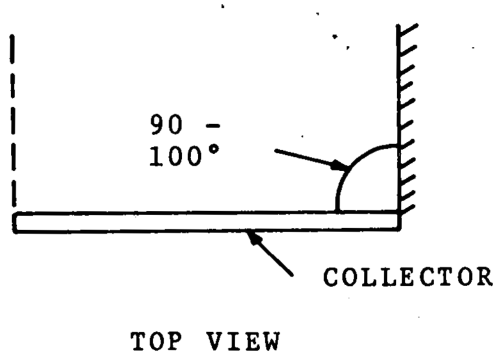
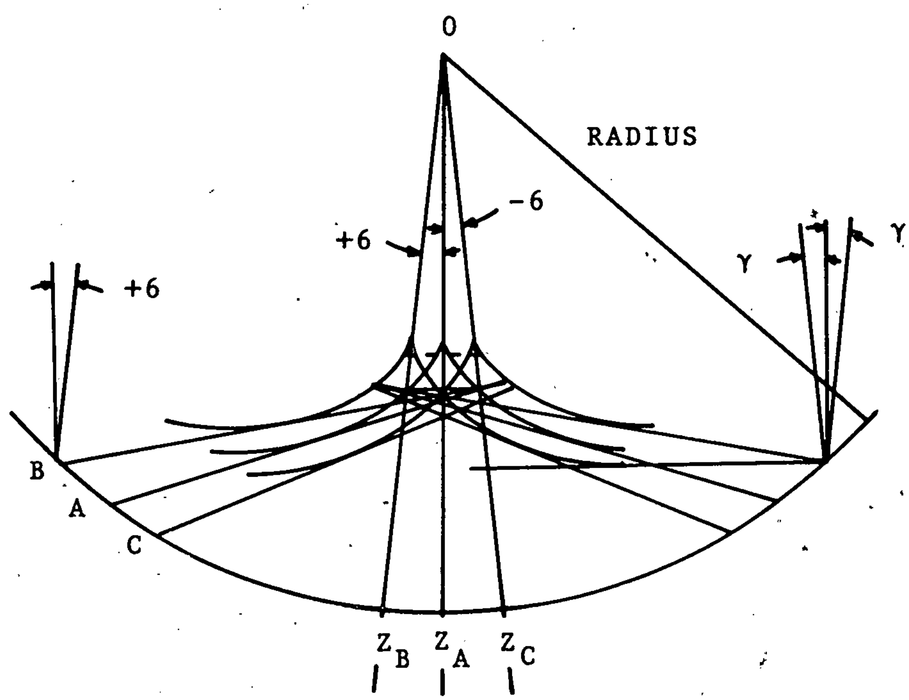


Figure 8. Noon-Reversing, Mirror Enhance, Flat-Plate Collector.



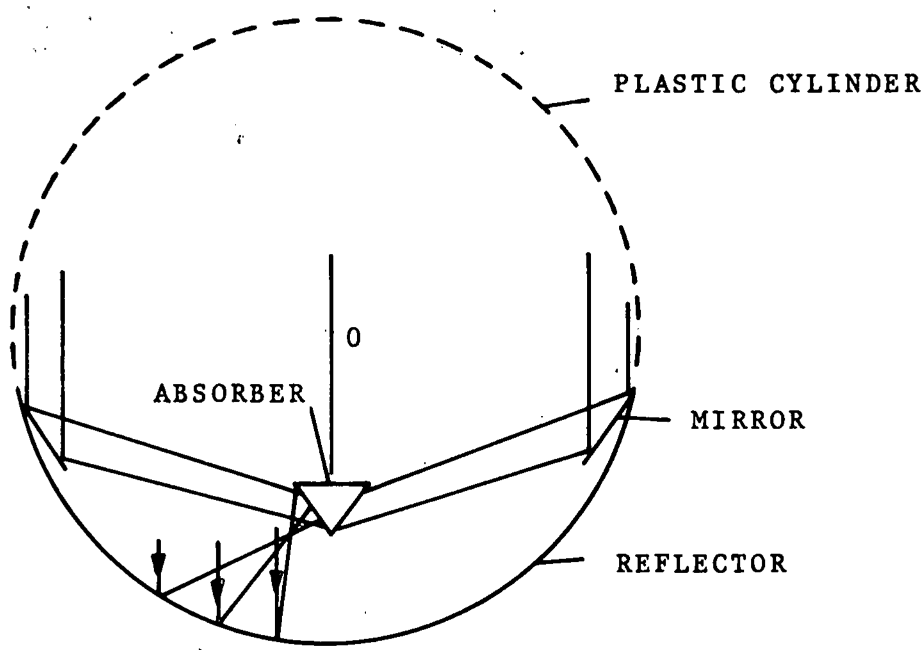


Figure 9. Inflated Cylinder, Focusing Collector.

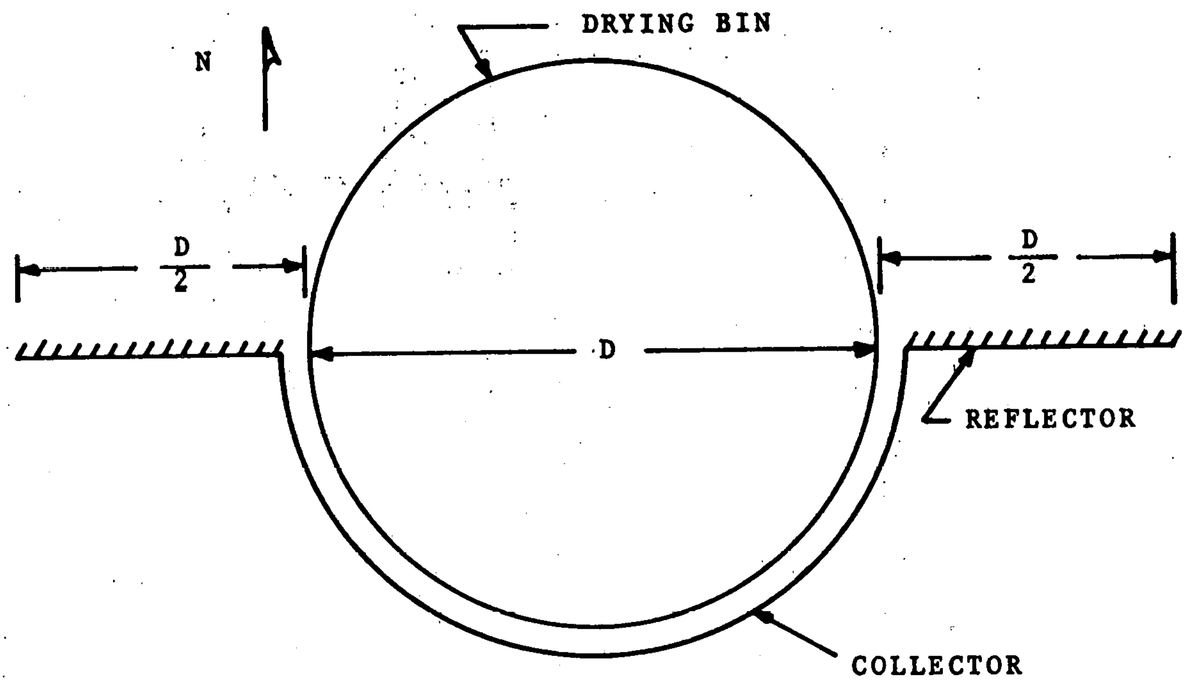


Figure 10. "Solar Wings", Used as a Concentrator on a Conventional "Wrap-Around" Solar Grain Drier.

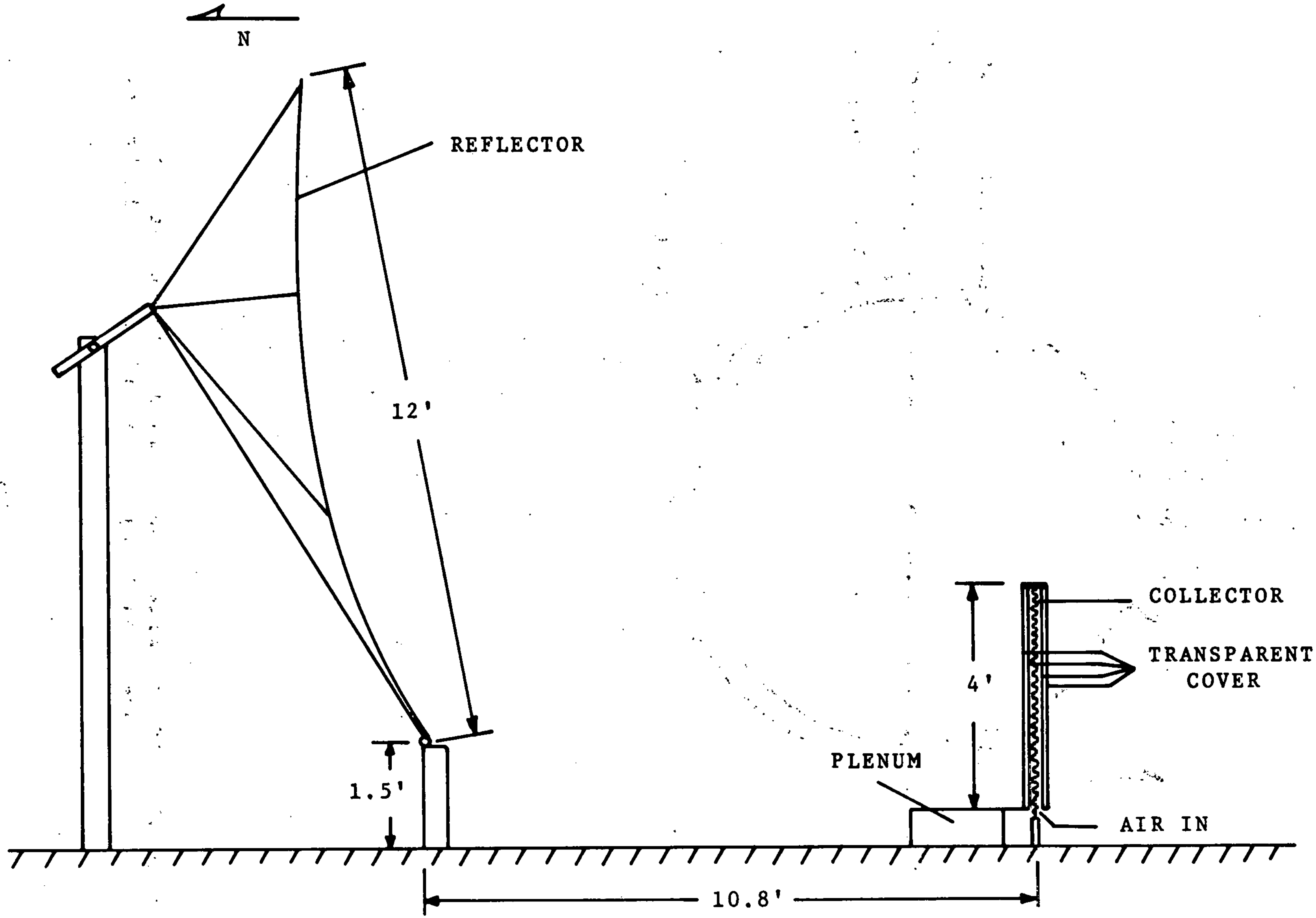


Figure 11. Profile of the SDSU Solar Energy-Intensifier System.

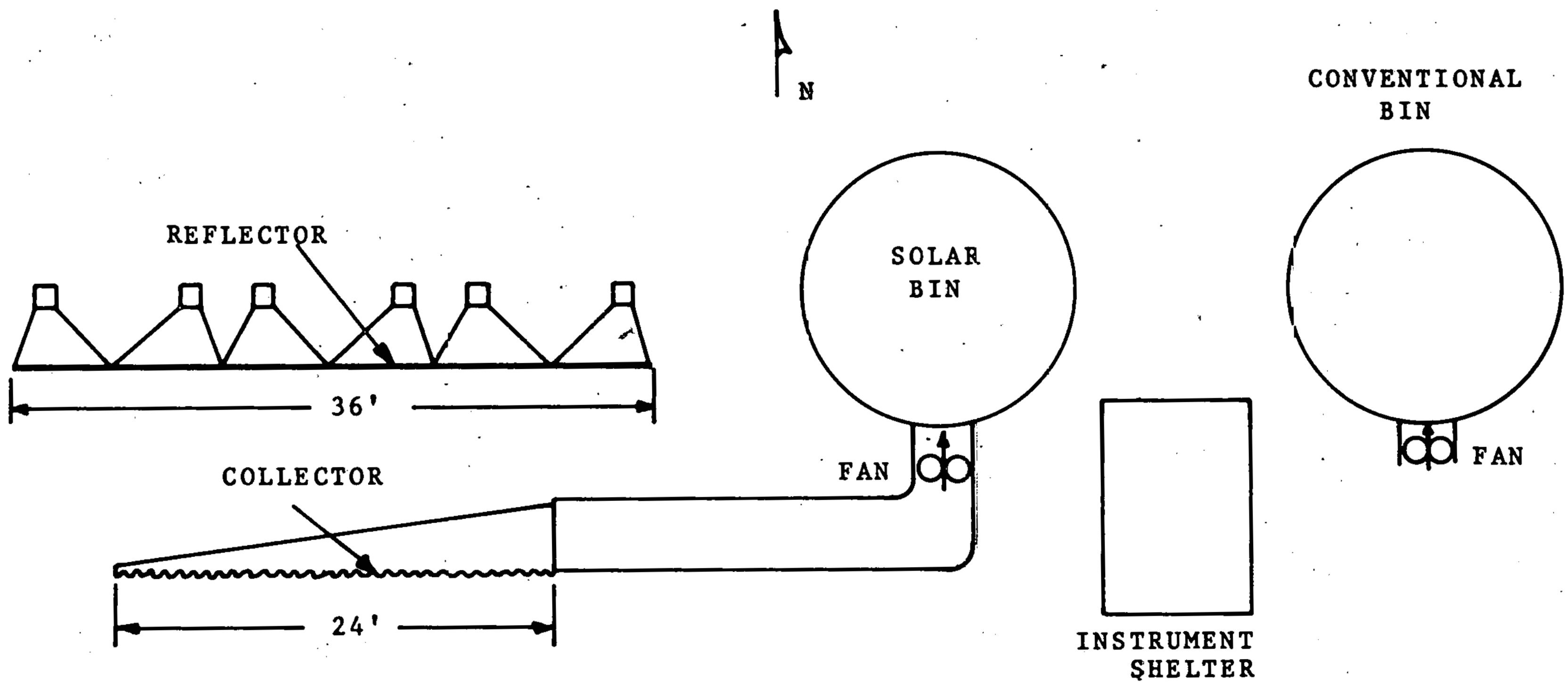


Figure 12. SDSU Solar Energy-Intensifier Grain Drying System, Top View.

WHERE DOES SOLAR GRAIN DRYING FIT?

T. L. Thompson and R. O. Pierce[1]

How much benefit can be obtained from solar energy for grain drying? Under what conditions will solar grain drying benefit my operation? Where is solar grain drying applicable? What airflow rate should I use? What are the limitations of solar grain drying? These are a few of the questions that have been raised concerning the application of using solar energy for the drying of grain.

Low temperature grain drying systems seem best adapted to take advantage of the relatively slow rate at which solar energy can be collected. Past research has not defined total system requirements for natural air grain drying or determined the effect of using small amount of continuous heat supplementation. An understanding of natural air grain drying is necessary to properly evaluate possible advantages of using solar energy in grain drying.

The grain drying performances presented in this paper were based upon the results from a detailed computer simulation study (1). Use of a computer simulation model (3) allowed us to predict drying results for ten years of tests at each of the states in the North Central Region of the United States.

The basic drying system studied consisted of a grain bin equipped with a full perforated floor, a fan, and either a heater to provide continuous supplemental heat or a solar collector designed for the drying bin. Using this setup, drying tests (simulation runs) were first made for the fall of 1974 at Lincoln, Nebraska using 24% moisture grain harvested on October 15. Figure 1 shows the average moisture content in the bin as the grain is dried for the period from October 15 to December 9 with an airflow rate of 1 cfm/bu. The figure also shows similar results using airflow rates of 2 and 3 cfm/bu. The grain is dried out faster at the higher airflow rates. From this graph, it is hard to determine which airflow rate does the best job of drying and how much airflow is actually required for this situation. To determine this airflow requirement we also need to consider the quality of the grain during drying, particularly with regard to spoilage of the grain at high moisture contents. Figure 2 presents a prediction of grain spoilage using a percent dry matter decomposition (% DM) value calculated from allowable storage times for corn (2,3). As a rule of thumb, the dry matter decomposition should be below one-half percent. For the drying situation represented in Figures 1 and 2, about 1.7 cfm/bu would be needed to dry the grain while keeping spoilage at an allowable level.

These results are for grain harvested at 24% on October 15, 1974 at Lincoln, Nebraska. How would this system perform in 1975? In 1976? Year-to-year variation in weather is a major factor in natural air grain drying.

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[1]Professor of Agricultural Engineering and Agricultural Engineer, University of Nebraska-Lincoln

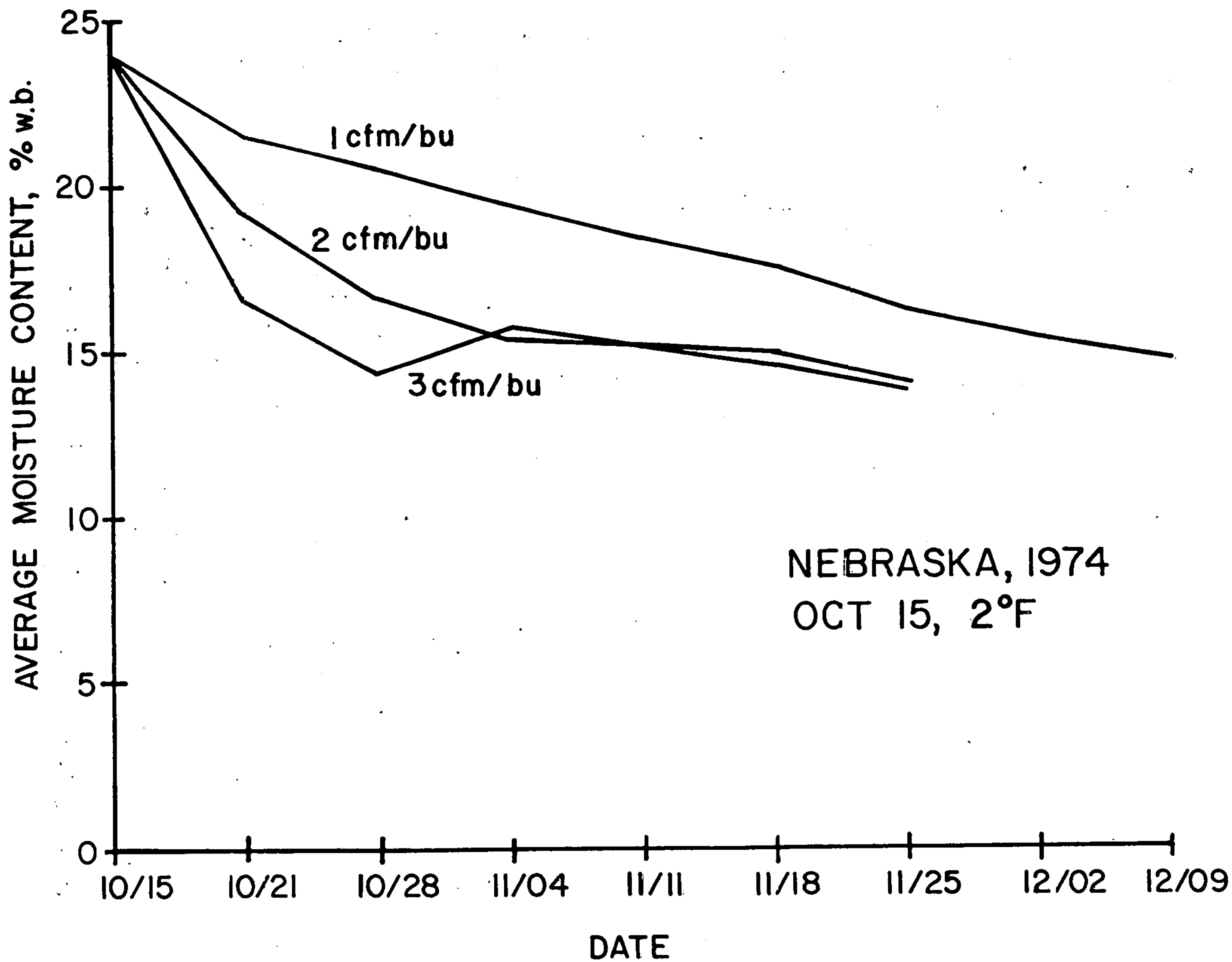

Figure 1. Drying Results with 3 airflow rates for 24% corn harvested October 15 at Lincoln, Nebraska.

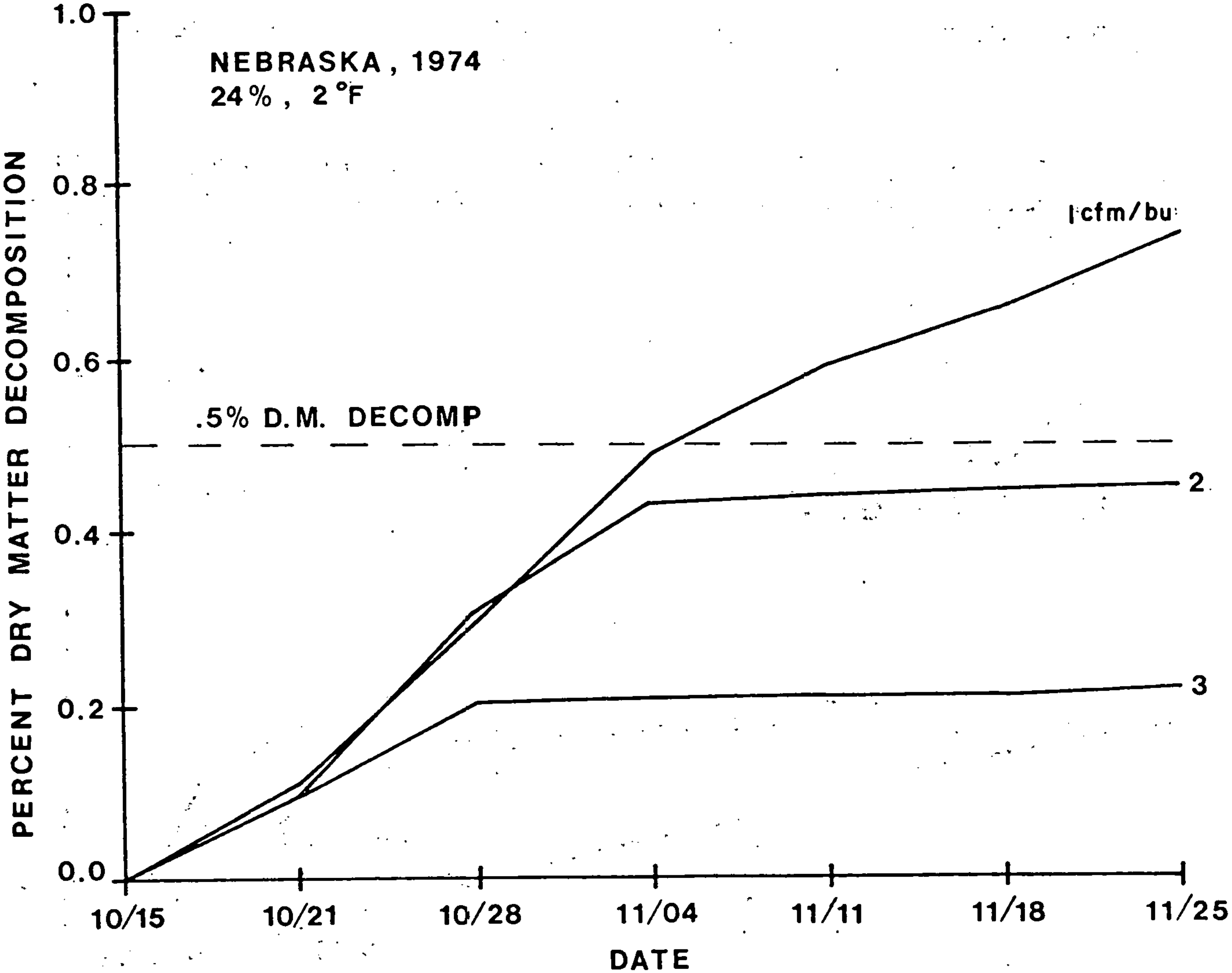

Figure 2. Effect of airflow rate on dry matter decomposition (24% corn, October 15 harvest date, Lincoln, Nebraska, Fall 1974).

Figure 3 shows the minimum airflow rates required at Lincoln for each of the years from 1960 thru 1974. These results indicate a wide variation in the amount of airflow needed from one year to the next. Much higher airflow rates were required for the years with unseasonable warm temperatures during the fall drying period, 1963 and 1971. These results show that it is very important to study system performance over many years to determine the worst possible conditions. A system which operates successfully for nine years may fail in the tenth. Generally, we do not like to make airflow recommendations based on results from less than ten years of actual weather data.

A more convenient manner of presenting these minimum airflow results is shown in Figure 4. These results are the same as those presented in Figure 3, but with the airflow rates plotted in increasing order. This essentially changes the plot of years (Y axis) into a probability axis. From this graph we can easily determine the airflow rate needed for successful operation ten years out of ten, nine years out of ten, or for whichever probability of success we would like to design. As an example, the dotted line shows that 2.3 cfm/bu is required for successful operation nine years out of ten for this particular situation (24% moisture corn harvested October 15 in Nebraska). We should point out that this value is the airflow rate "delivered". There is no safety factor included in this airflow rate and the results do not represent the airflow rate designed for but that actually delivered to the bin.

How much can airflow requirements be reduced by adding supplemental heat to the drying air? The effects of four levels of supplemental heat on minimum airflow requirements are shown in Figure 5. The curve labeled $0^{o}F$ represents a suction type airflow system and indicates what airflow rates would be required if no supplemental heat is added. The $2^{o}F$ curve represents a positive airflow system where the $2^{o}F$ temperature rise can typically be obtained by pulling the air over the fan motor. The two curves on the left represent systems picking up $2^{o}F$ of heat from the fan motor plus an additional 3 and $6^{o}F$ from a continuous heat source such as an electrical heater. There is very little difference in the airflow requirements for the systems picking up at least $2^{o}F$ of supplemental heat. This does not mean that there are no benefits from adding supplemental heat. It does mean that the addition of supplemental heat (over that provided by the fan motor) does not significantly reduce airflow requirements.

A similar set of results are presented in Figure 6 for systems where supplemental heat was provided by pulling the air over the fan motor ($2^{o}F$) and using various levels of solar supplementation. Daily radiation data were used to determine the amount of solar supplemental heat (temperature rise of the drying air) that was provided by the solar collector for each day. In very general terms, the five levels of solar supplementation shown (when operating at 2 cfm/bu) are represented by zero, one-fourth, one-half, three-fourths and one square foot of collector per bushel of grain in the bin. Generally, these results show that the airflow requirements cannot be reduced by using solar supplementation to heat the drying air.

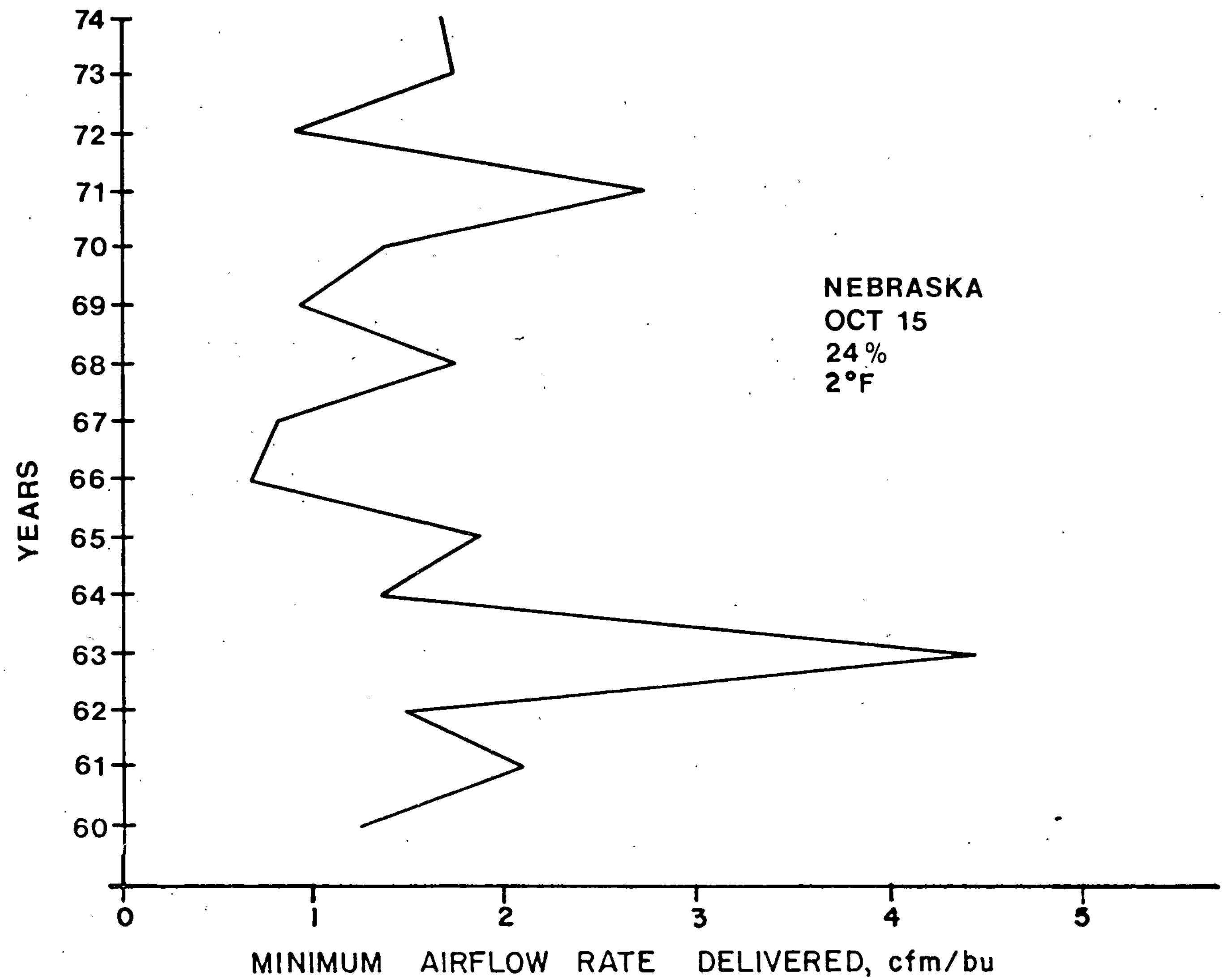

Figure 3. Year-to-year variations in the airflow rate required to dry 24% corn, harvested October 15 at Lincoln, Nebraska, with less than .5 percent dry matter decomposition (a 2°F temperature rise from the fan motor was assumed).

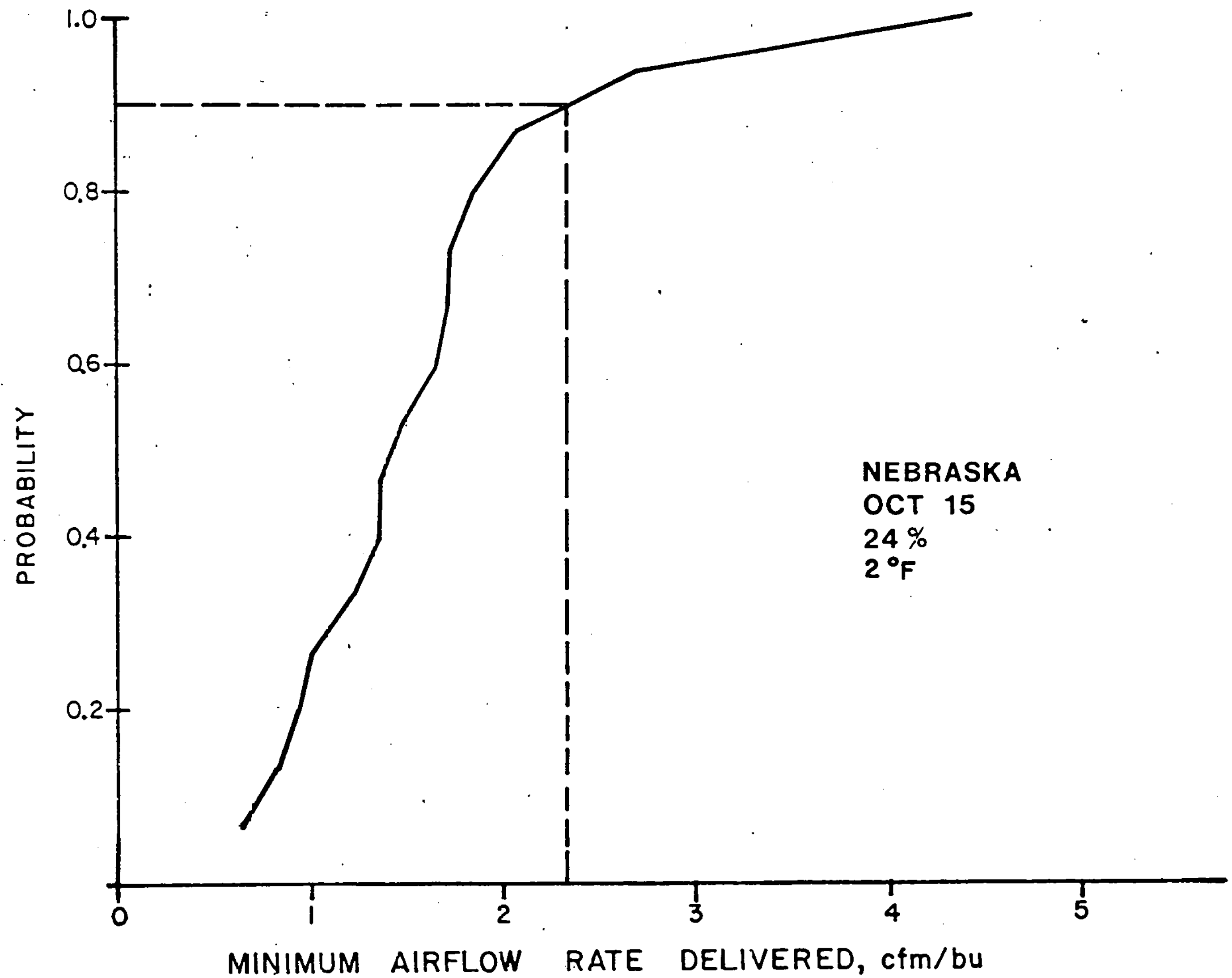

Figure 4. Minimum airflow required to dry 24% corn, harvested October 15 at Lincoln, Nebraska, expressed on a probability basis. (a 2°F temperature rise from the fan motor was assumed).

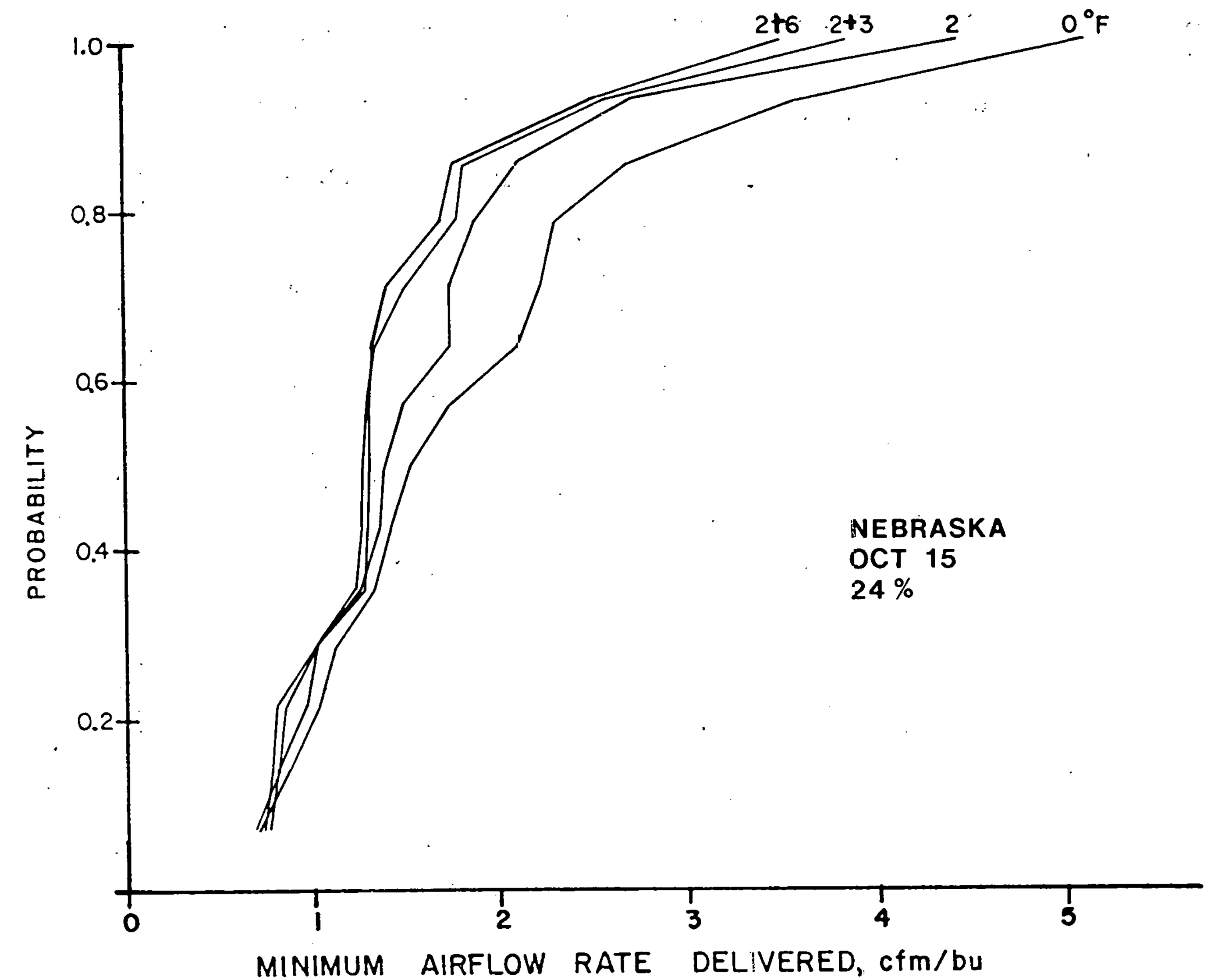

Figure 5. Effect of various levels of continuous heat on the airflow required to dry 24% corn harvested October 15 at Lincoln, Nebraska.

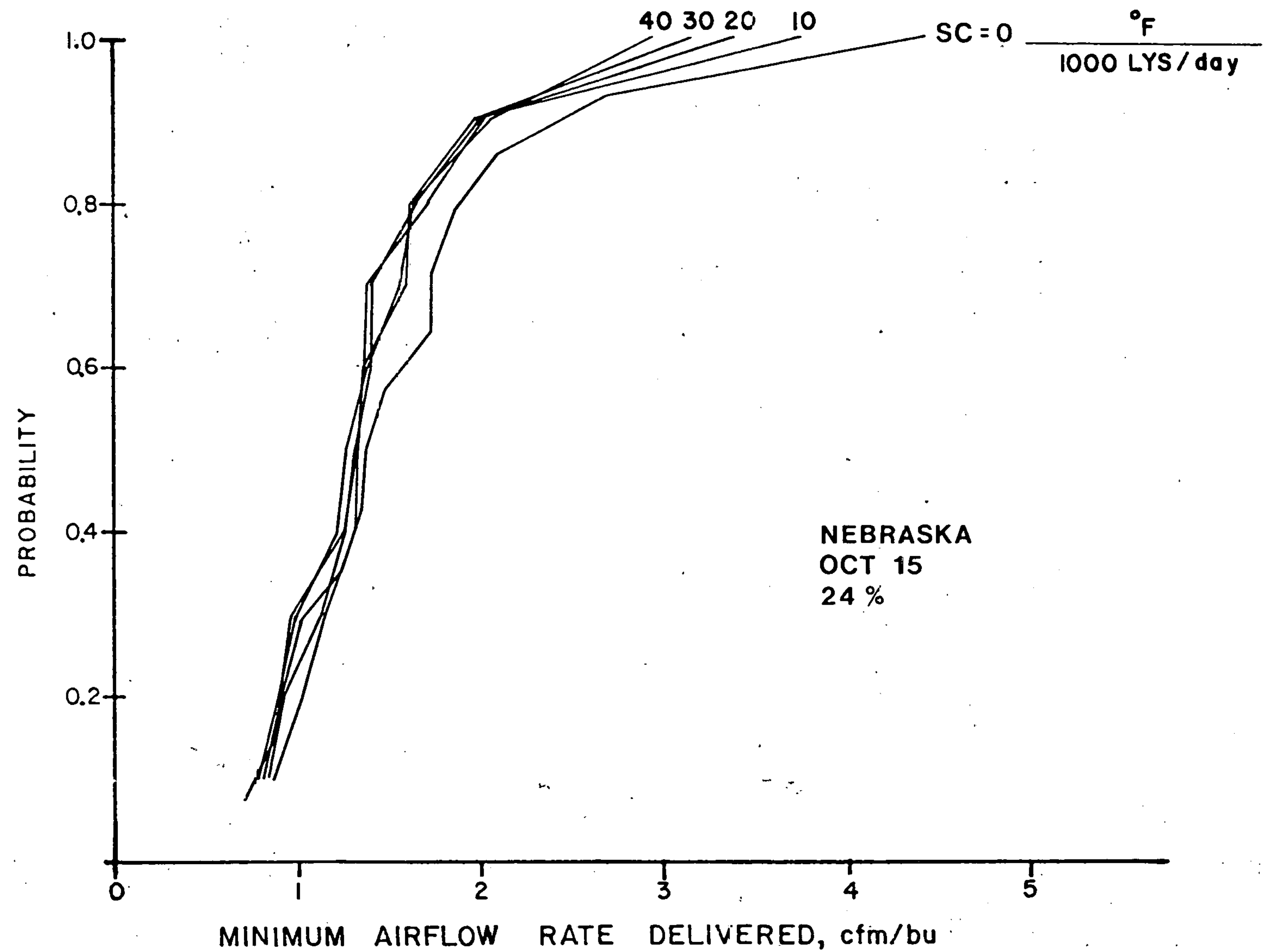

Figure 6. Effect of 5 levels of solar supplementation on the airflow required to dry 24% corn harvested October 15 at Lincoln, Nebraska.

In more technical terms, the solar collector coefficients shown on this graph were selected to represent a collector size capable of providing a given temperature rise per unit of radiation received. This coefficient was defined as the "average 24 hour temperature rise that a solar collector will produce when receiving 1000 langleys of solar radiation per day". This definition makes the coefficient independent of airflow rate and collector efficiency. For example, assuming a solar collector coefficient of 10 and solar insolation of 300 langleys/day, the 24 hour average temperature would be calculated as 10(300)/1000 or 3°F.

One advantage of adding supplemental heat is that the time required to dry the grain is reduced. Figure 7 shows the date drying was completed using the minimum airflow rates for each year. These results clearly indicate that when we add supplemental heat (above the 2°F obtained by pulling the air over the fan motor) the probability of completing drying in the fall is much greater than when no supplemental heat is added.

What is the effect of initial moisture content on airflow requirements? Figure 8 shows that airflow rates need to be increased when the harvest moisture content is increased. As a rough rule of thumb, for each 2% increase in moisture content the airflow rate should be doubled. Likewise, for each 2% decrease in moisture content the airflow rate can be halved. But this is only true down to about .75 cfm/bu. There may be problems when operating at the low airflow rates indicated for the lower initial moisture contents. For airflow rates below .75 cfm/bu, there is generally not enough air volume to effectively remove moisture from the grain and it should be considered to be an aeration or holding airflow rate.

The above results are only applicable for Lincoln, Nebraska conditions. A similar series of tests (simulation runs) were made for one location in each state in the North Central Region. Table 1 lists each of these locations and also indicates the years of weather and radiation data that were used for this study. These locations were selected to represent the grain drying areas of each state, but were limited to some extent by the availability of radiation and weather data. The simulation results for most locations were similar to those shown above for Lincoln. It was generally concluded that airflow rates could not be significantly reduced by adding continuous or solar supplemental heat (above the 2°F from the fan). The only exception to this conclusion was for Indiana and Ohio conditions. Minimum airflow results using Indianapolis weather inputs with four levels of continuous supplemental heat are shown in Figure 9. The airflows required with 2°F of heat from the fan are considerably higher than the airflows required if an additional 3°F of continuous supplemental heat is added. Similar results were noted for Ohio. These higher airflow requirements were probably due to the warmer higher humidity conditions in these two states.

A comparison of the minimum airflow rates across the North Central region is shown in Figure 10. These airflow rates were determined for a system operating with no supplemental heat other than the 2°F from the fan motor.

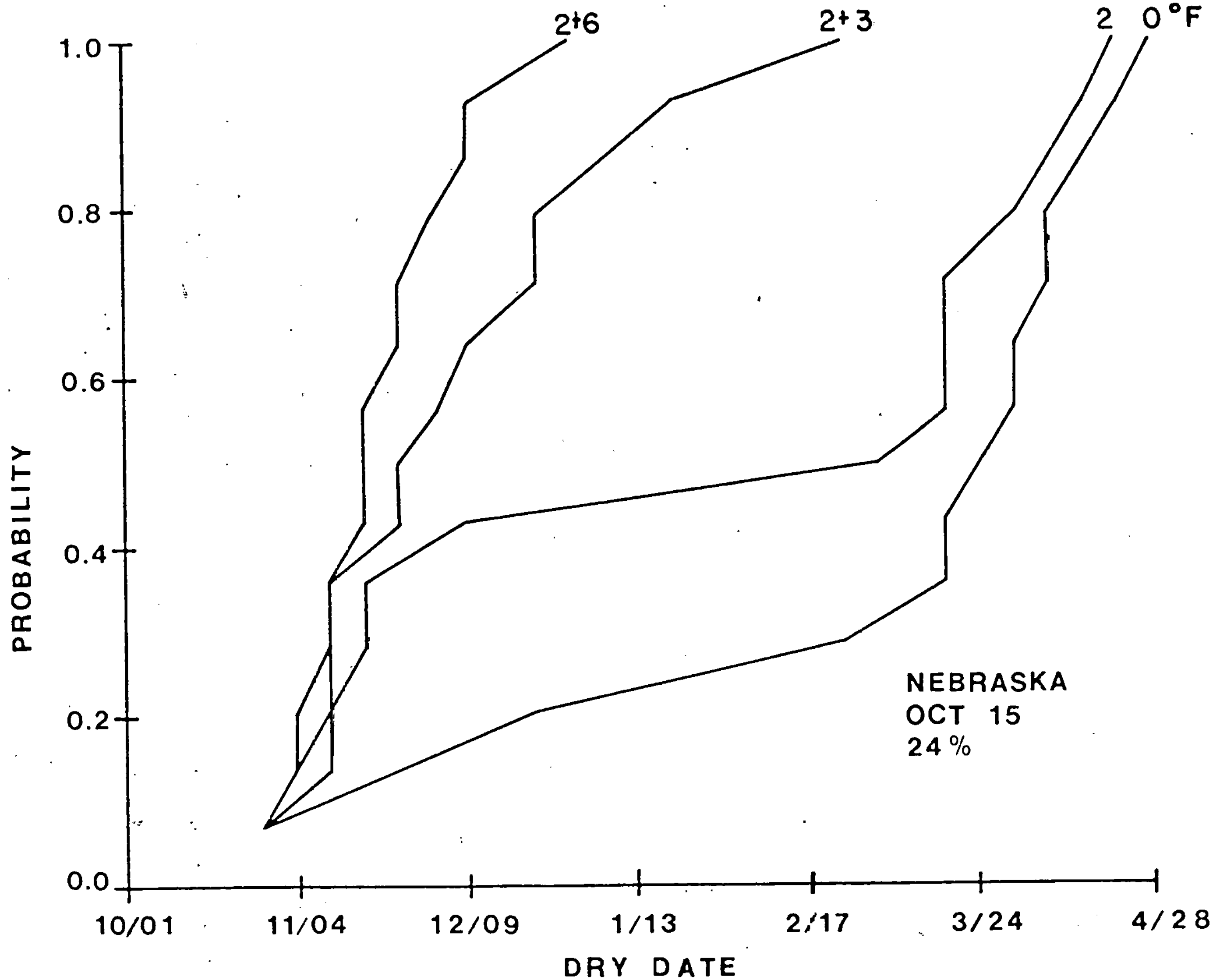

Figure 7. Effect of various levels of continuous heat on the date by which 24% corn harvested October 15 at Lincoln, Nebraska can be dried using the minimum airflow rates.

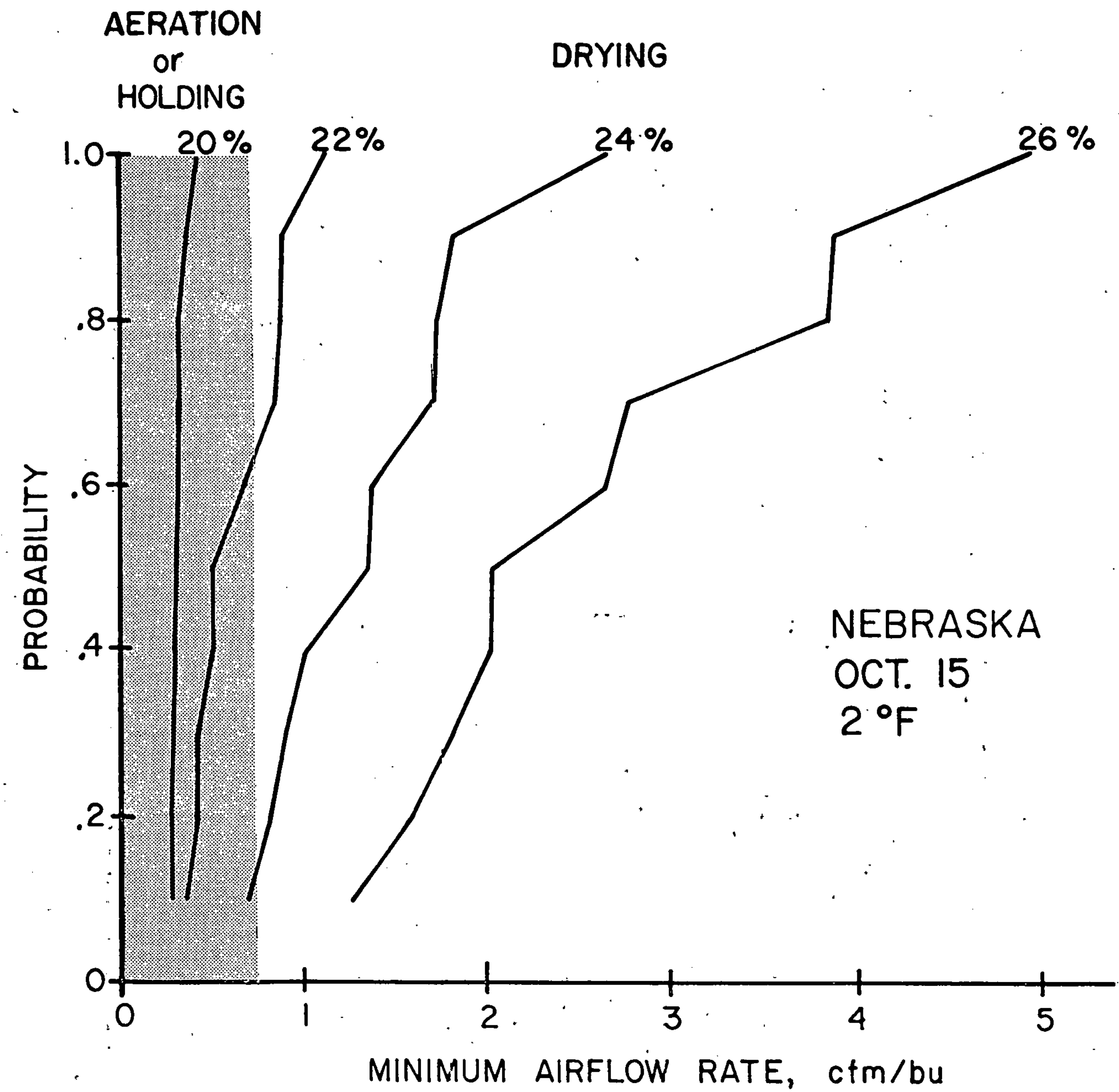

Figure 8. Effect of harvest moisture content on the airflow rate required to dry corn harvested October 15 at Lincoln, Nebraska.

Table 1. Summary of North Central Region data availability and locations selected for this study.

State	Temperature Data Location	Temperature Data Available	Radiation Data Location	Radiation Data Available[1]	Fall Periods Used
North Dakota	Bismarck	1948-73	Bismarck	1950-69	1960-69
South Dakota	Huron	1940-74	Brookings	1961-74	1962-64, 1966-71, 1973
Nebraska	Lincoln	1954-75	Omaha	1957-69	1960-69
Kansas	Dodge City	1948-73	Dodge City	1952-69	1960-69
Minnesota	St. Cloud	1948-71	St. Cloud	1954-69	1954, 1956-57, 1962-65, 1967-69
Iowa	Des Moines	1945-72	Ames	1959-69	1959-65, 1967-69
Missouri	Columbia	1945-72	Columbia	1944-69	1960-69
Wisconsin	Madison	1948-73	Madison	1952-61, 1963-69	1952-56, 1965-69
Illinois	Chicago/O'Hare	1959-73	Lemont	1957-69	1959-65, 1967-69
Indiana	Indianapolis	1952-60, 1965-72	Indianapolis	1951-69	1952-54, 1958-60, 1966-69
Michigan	Lansing	1949-53, 1959-73	E. Lansing	1953-69	1953, 1959-67
Ohio	Mansfield	1963-67, 1969-73	Wooster	1963-74	1963-67, 1969-73

[1] The radiation data may not be complete for the period indicated.

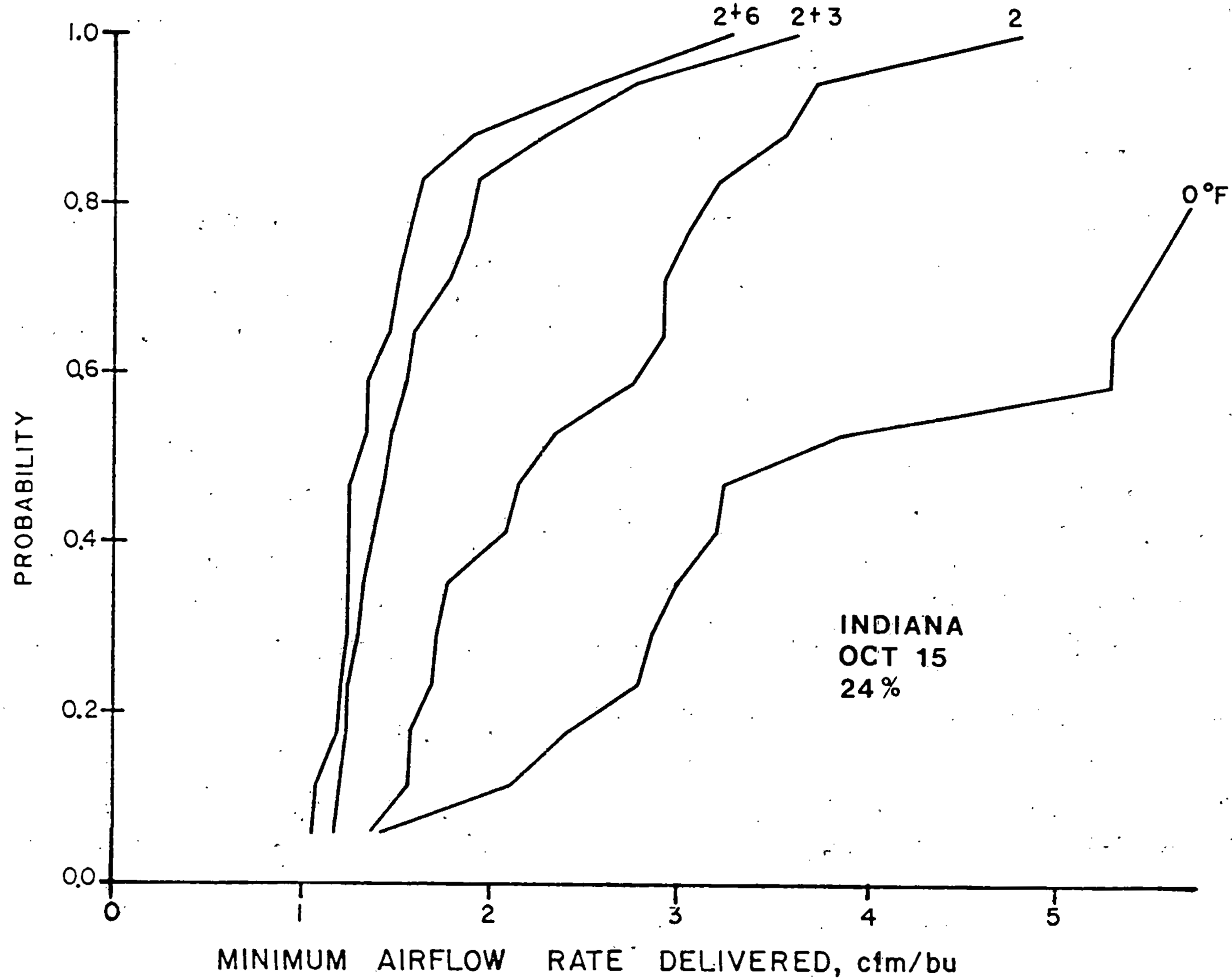

Figure 9. Effect of various levels of continuous heat on the airflow required to dry 24% corn harvested October 15 at Indianapolis, Indiana.

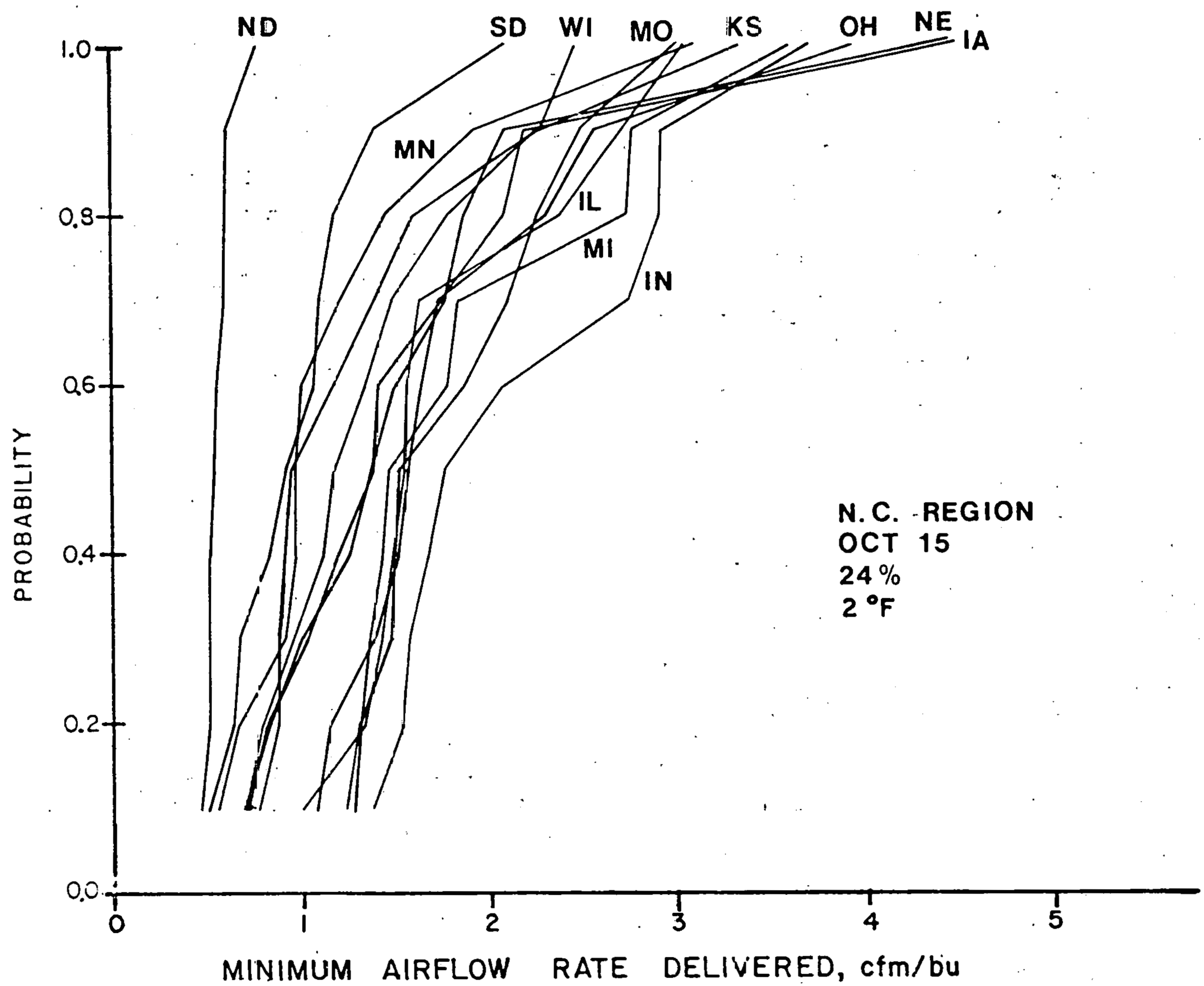

Figure 10. Predicted airflow requirements for the various locations across the North Central Region (2°F temperature rise from the fan motor, 24% corn and an October 15 harvest were assumed).

It is hard to visualize the relationship between airflow requirements for the various states represented on this graph. These results are summarized in Figure 11 by considering only the airflow requirements for the next to worst year. This plot shows how minimum airflow requirements increase as you move from the north western section of the region (North Dakota) down to the higher temperature and humidity areas of Indiana and Ohio. Airflow requirements ranged from 1 to 3 cfm/bu across the region.

Drying times also varied widely across the region. Figure 12 compares the dry dates for the various locations using the minimum airflow rates required for each year. Basically, this shows that drying is slower for the cooler and/or more humid climates and generally not completed until late spring or early summer. For the southern states of the region, drying is typically completed in the fall. The intermediate corn belt states can generally expect to complete drying in the fall approximately 50% of the time. The probability of completing drying in the fall is increased with the addition of supplemental heat.

At this point, it should be emphasized that the airflow rate is the most important factor in designing and operating low temperature grain drying systems regardless of whether natural air, continuous supplemental heat or solar supplementation is used. In most cases, if a system is not designed for the proper airflow rate the addition of supplemental heat will increase the amount of spoilage. Or stating it another way, the additional heat will many times just warm the grain so that it spoils faster, if there is not enough airflow.

The results presented above can be used to design a system which will 'work', but do not indicate the most energy efficient method of drying the grain. The results shown above were with continuous fan operation until all of the grain was dried below 15% moisture. Some of the drying experiments were not completed until the following spring. Considerable energy savings are possible if the fan is operated intermittently during the winter months when drying potential is low.

We approached this problem by plotting the average temperature conditions and the equilibrium moisture contents for each two week period thoughout the year. An oversimplified plot of these results for central Iowa is shown in Figure 13. A period of very low temperatures and high equilibrium moisture contents is indicated from approximately the first of December until the middle of March. Consequently, we studied a fan operating schedule of 1) running the fan continuously until December 1, 2) operating it for two hours per day during the winter months to equalize temperatures within the bin and to prevent the development of hot spots and 3) beginning the middle of March, operating the fan continuously when temperatures are above 55°F and continuing this practice until the grain was dried.

A wide range of grain drying conditions were studied for central Iowa conditions to aid in evaluating the benefits of using continuous or solar energy for corn drying. A summary of drying results using weather data inputs from 1959-69 are shown in Table 2. These results are for 22% corn

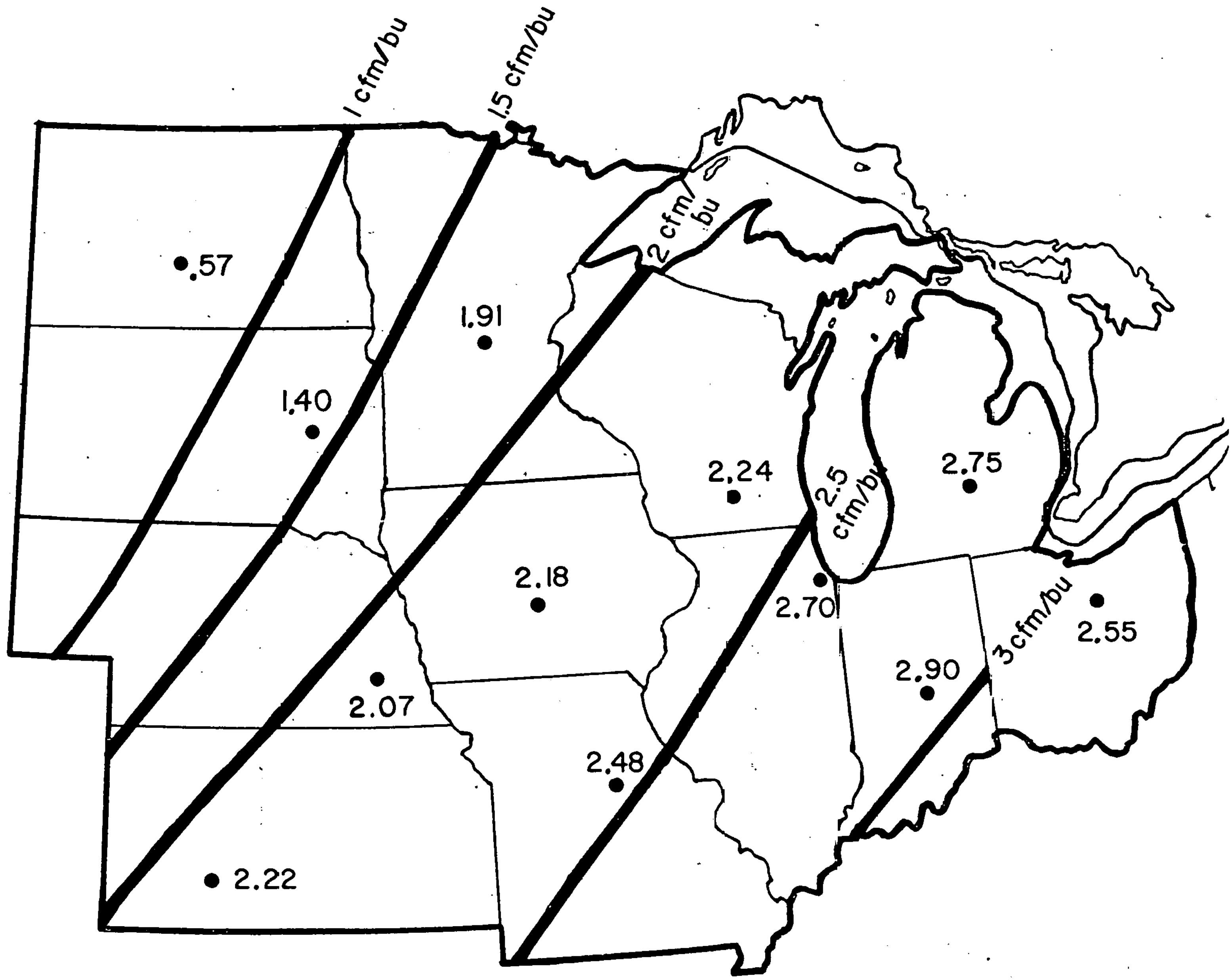

Figure 11. Minimum airflow rates required for successful drying 9 years out of 10 assuming 24% corn harvest October 15 for each of the North Central Region states. (A 2°F temperature rise from the fan motor was assumed.)

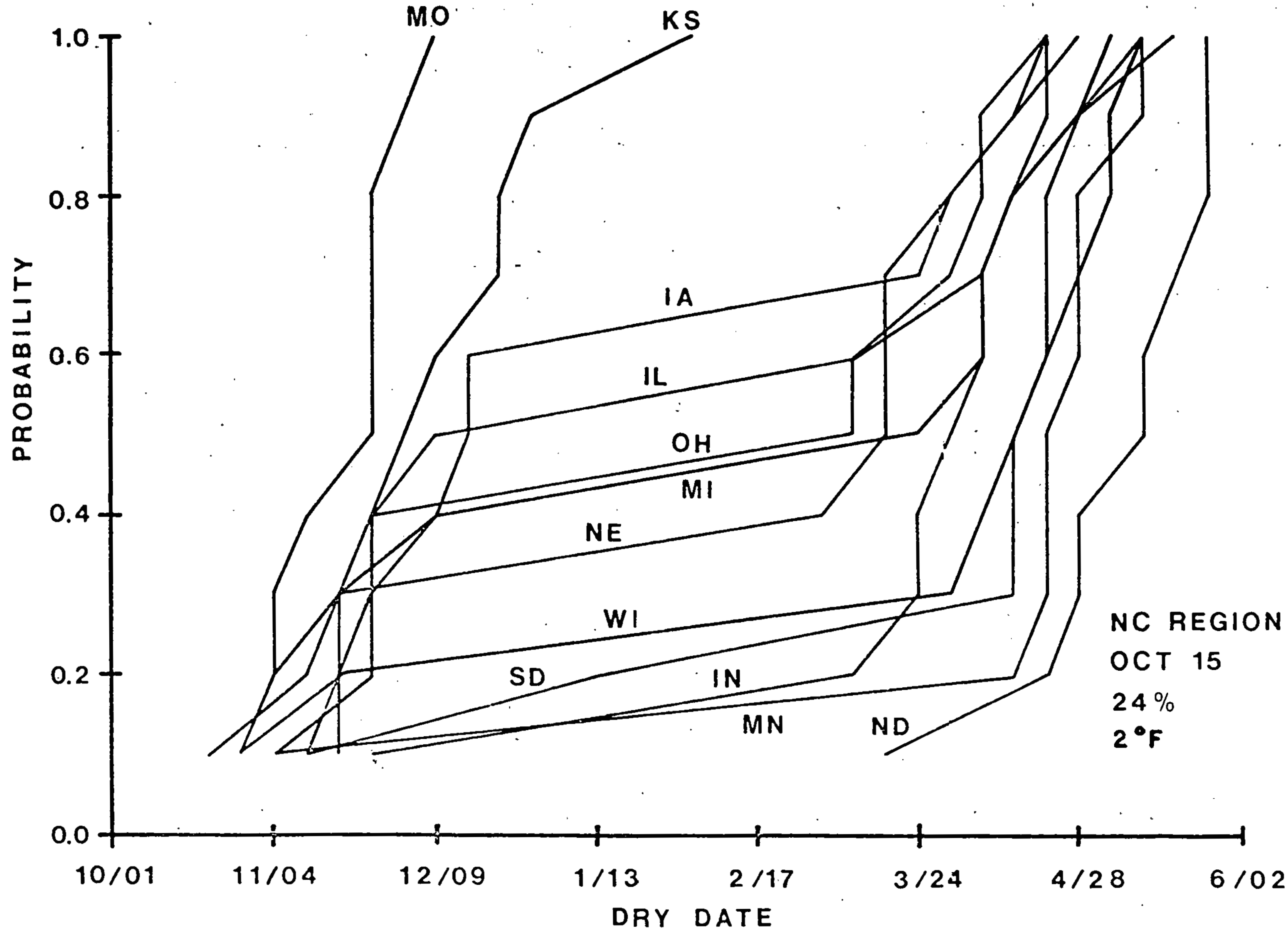

Figure 12. Predicted dry dates for the various locations across the North Central Region assuming a 2°F temperature rise from the fan, 24% corn and an October 15 harvest.

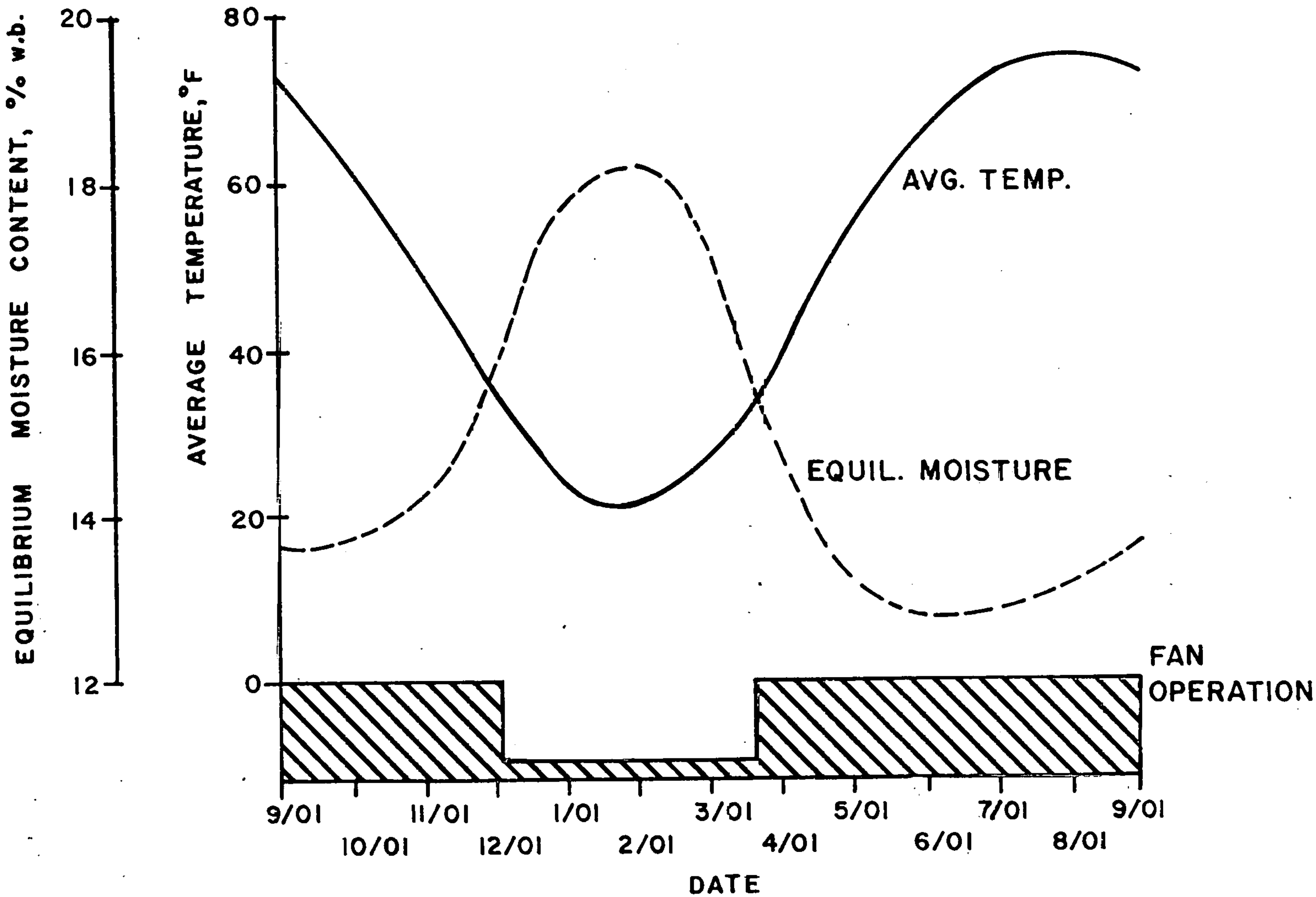

Figure 13. Average temperature conditions and equilibrium moisture contents for central Iowa.

Table 2. A summary of predicted drying results for a ten-year period at Des Moines, Iowa. Simulation runs were made with an airflow rate of 1.3 cfm/bu, 22% corn and an October 15 harvest date.

Natural Air (2°F)

Condition	Minimum	Average	Maximum
Final Moisture, % w.b.	11.5	13.4	14.5
% Dry Matter Decomposition	.173	.342	.618
Fan Hours	864	1235	1882
Dry Date	11/18		5/05

Continuous Heat (2 + 3°F)

Condition	Minimum	Average	Maximum
Final Moisture, % w.b.	12.2	13.0	14.0
% Dry Matter Decomposition	.174	.307	.619
Fan Hours	696	864	1032
Heater Hours	696	864	1032
Dry Date	11/11		11/25

Solar Drying (2°F + Solar[1])

Condition	Minimum	Average	Maximum
Final Moisture, % w.b.	9.7	13.0	14.2
% Dry Matter Decompostion	.172	.314	.618
Fan Hours	696	1032	1882
Dry Date	11/11		5/05

[1] Using a solar collector coefficient of 10°F/1000 langleys/day

harvested on October 15 and dried with an airflow rate of 1.3 cfm/bu. This airflow rate was selected (from a graph similar to Figure 5) to allow for successful drying nine years out of ten, assuming a 2°F temperature rise from the fan motor. Direct comparisons between the different systems are difficult because of the number of factors involved. Costs were calculated for each of these factors and used as a common basis of comparison between the systems. The total drying cost included fixed costs for the bin and equipment, energy costs for operating the fan and providing continuous supplemental heat, the cost of a solar collector and penalty costs for overdrying and excessive spoiling of the grain.

The fan energy requirements and fixed costs for equipment are very dependent upon the specific dryer configuration used. The results from any cost comparison are also greatly influenced by the costs assigned for each factor. Figures 14, 15 and 16 show drying costs for a 24 foot diameter bin holding 6000 bushels of corn. The fan operating costs (@$0.03/kW-hr) can be calculated knowing the size of the fan required for this specific situation (9 HP) and the hours of fan operation. Heat energy costs are dependent upon the desired temperature rise (heater size) and hours of heater operation. Overdrying costs were calculated using the average final moisture content to determine the weight loss below 15.5% w.b.. The spoilage penalty costs were based on an arbitrary exponentially increasing function with a rapidly increasing penalty for final dry matter decomposition above one-half percent. A grain price of $2.80/bu was used in calculating overdrying and spoilage penalties.

Drying costs for the system operated with no supplemental heat are presented in Figure 14. A comparison of the overall drying costs for the individual years indicates a 50% increase in costs from the lowest to the highest values. This year-to-year variation was largely dependent on the date by which drying was completed.

A similar set of drying costs for the system operated with 3°F of continuous heat are presented in Figure 15. Although there was an overall reduction in fan energy and spoilage costs, the average drying costs were increased due to higher overdrying costs and the addition of heat energy costs. Comparing the results from Figures 14 and 15, the year-to-year drying costs are more uniform for the system operated with supplemental heat. This comparison also shows that the addition of supplemental heat did not cause an increase in drying costs for every year. For example, drying costs for 1959 were reduced from 26 to 23 ¢/bu with the addition of continuous heat. It was typical of these results that neither of the drying strategies proved superior for each of the ten years studied.

Figure 16 presents drying costs using a solar collector of .18 ft^2/bu (assuming a 50% efficiency) instead of a continuous heat source. Although the generalized drying results (Table 2) were approximately the same for the solar and continuous heat tests, the average drying costs are considerably higher for the solar supplemented system. The major factor increasing these costs over those shown in Figures 14 and 15 was the cost of the solar collector. This collector costs (10.8 ¢/bu) was based upon

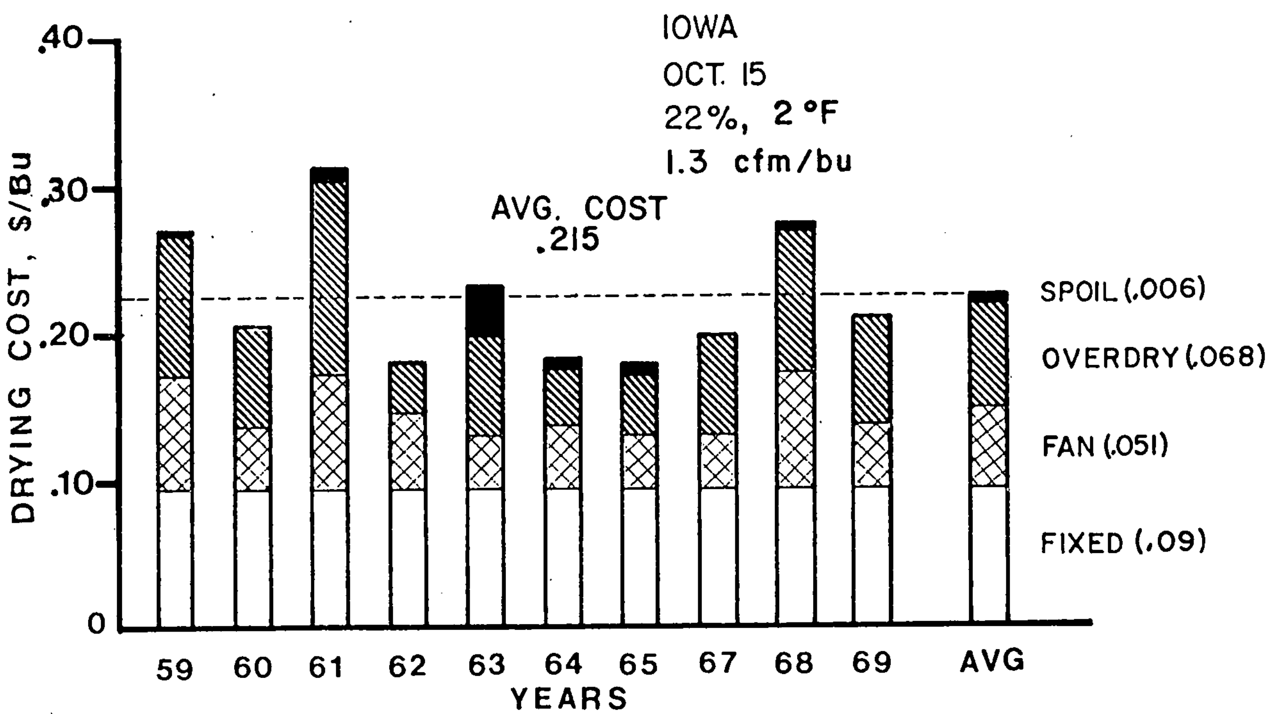

Figure 14. Predicted drying costs for central Iowa for 1959 thru 1969, assuming 22% corn harvested October 15 and dried with 1.3 cfm/bu. A $2^{o}F$ temperature rise from the fan was assumed.

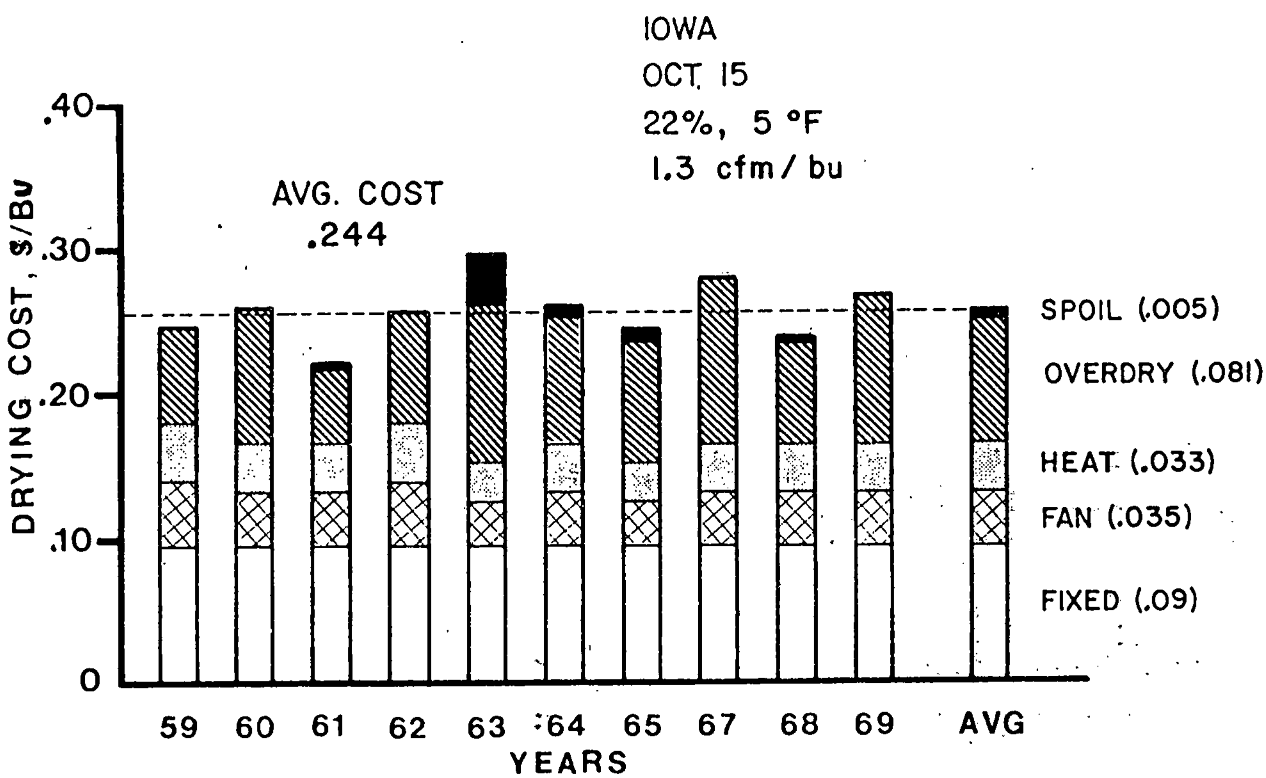

Figure 15. Predicted drying costs for central Iowa for 1959 thru 1969, assuming 22% corn harvested October 15 and dried with air heated by $3^{o}F$ of continuous heat (in addition to the $2^{o}F$ from the fan) and delivered at the rate of 1.3 cfm/bu.

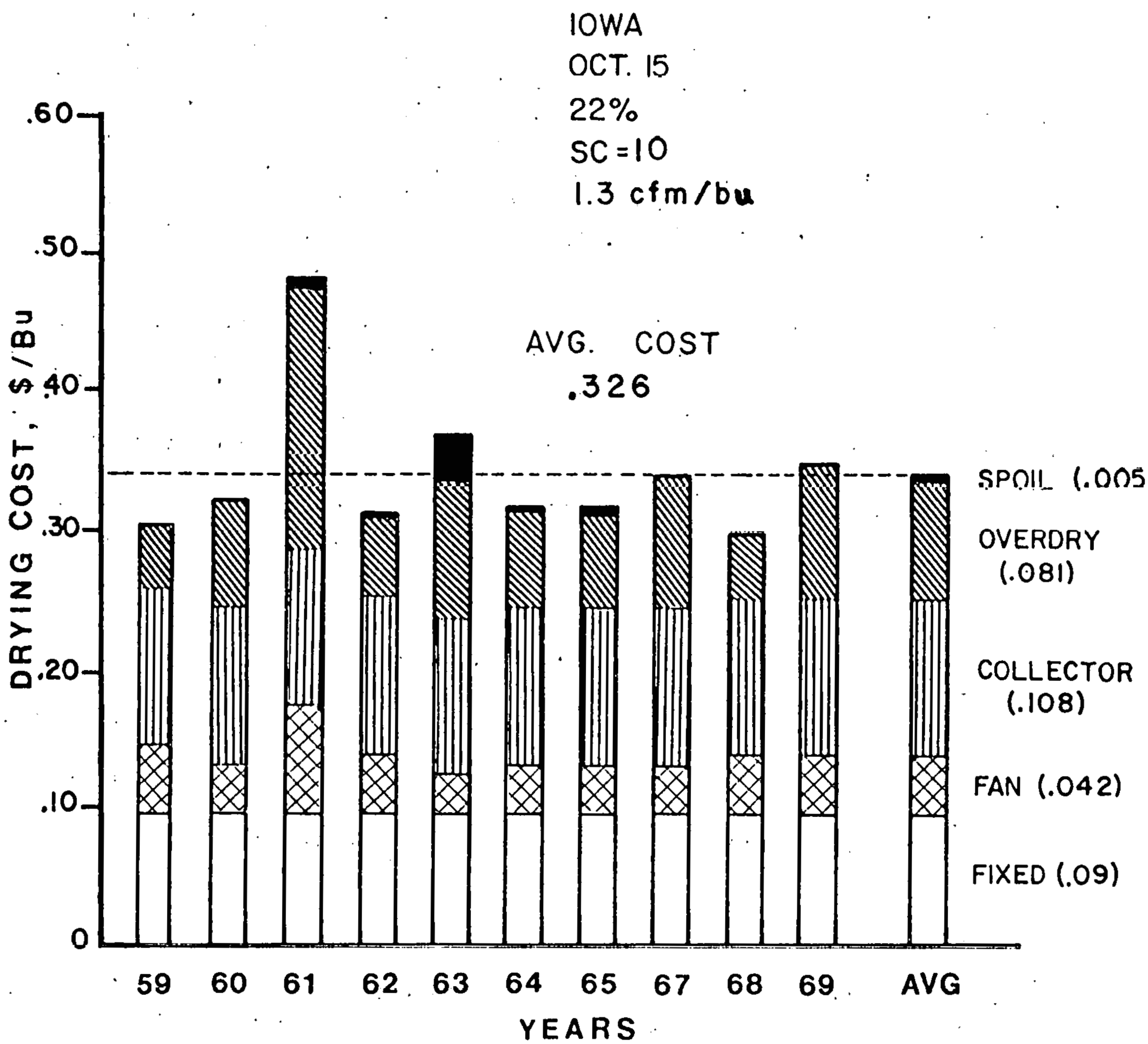

Figure 16. Predicted drying costs for central Iowa for 1959 thru 1969, assuming 22% corn harvested October 15 and dried with solar heated air ($10^{o}F$/1000 langleys/day) and delivered at the rate of 1.3 cfm/bu.

an initial cost of $\$1.50/ft^2$, a three year life and a ten percent interest rate. Collector drying costs for other initial collector costs and economic lifes are shown in Table 3.

It is important to remember that these cost figures were calculated for a specific drying situation in central Iowa. Fan energy costs and fixed costs per bushel will be affected by changing the bin configuration or varying the number of bushels of grain held in the bin. The effect on drying cost of varying the amount of grain dried in a 24 foot diameter bin is shown in Figure 17. Drying costs vary widely for capacities ranging from 3000 - 10000 bushels. At low capacities, drying costs are high because the fixed cost per bushel is high as the grain depth is increased, fan horsepower requirements increase exponentially, which cause a corresponding increase in drying cost.

Drying performance, and therefore drying cost, is affected by harvest date and initial moisture content. Additional drying tests were made for October 1 and November 1 harvest dates with an initial moisture content of 22% w.b.. These tests were repeated for a system designed to dry 24% corn with 2.3 cfm/bu. Average drying costs (using the same costs as above) calculated from these results are presented in Table 4. The drying costs are considerably higher when drying 24% corn. Drying costs were generally lowest when no supplemental heat was added (above the 2^oF from the fan motor), but there were some situations where they were lower by adding 3^oF of continuous heat.

Total costs for the solar drying systems were much higher due to cost of the collector. There is a need for the development of collectors with lower initial costs and longer lives. The economic picture could be drastically altered by rapidly increasing fuel costs and supply problems. From the Iowa results presented in Tables 3 and 4, it appears that in some instances the solar drying system would be competitive with the 3^oF continuous heat system if collector costs could be reduced to 6¢/bu or if electrical rates increased to $.10/kW-hr.

CONCLUSIONS

Selection of an airflow rate is the most important factor in designing a low temperature drying system. A simulation model was used to determine the minimum airflow rates required for low temperature drying in the North Central Region of the United States. Ten years of actual weather data were used in the simulation model for one location in each of the North Central states. The results indicated that:

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

2) Generally, the minimum airflow rate required is not significantly reduced by adding supplemental heat above the approximate 2^oF temperature rise that can be obtained by pulling the air over the fan motor.

The exceptions were central Indiana and Ohio where an additional 3°F did reduce the required airflow rate.

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

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

Results for a specific drying system in central Iowa, using a fan management procedure to reduce fan energy requirements, indicated the following:

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

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

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

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

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

Similar studies are in the process of being made for the varying conditions over the North Central region.

Table 3. Effect of initial collector cost ($\$/ft^2$) and economic life on collector drying costs. These cost figures are based upon a 1097 ft^2 collector which will provide 10^oF/1000 langley/day with an airflow rate of 1.3 cfm/bu (6000 bushels assumed).

Collector Cost ($\$/ft^2$)	Economic Life (Years) 1	2	3	5	10	15	20
.50	9.7	5.1	3.6	2.4	1.5	1.2	1.0
.75	14.5	7.7	5.4	3.6	2.2	1.7	1.5
1.00	19.4	10.2	7.2	4.8	2.9	2.3	2.0
1.50	29.1	15.4	10.8	7.1	4.4	3.5	3.0
2.00	38.7	20.5	14.4	9.5	5.8	4.6	4.0
3.00	58.1	30.7	21.6	14.3	8.8	6.9	6.0
4.00	77.5	40.9	28.8	19.0	11.7	9.3	8.0

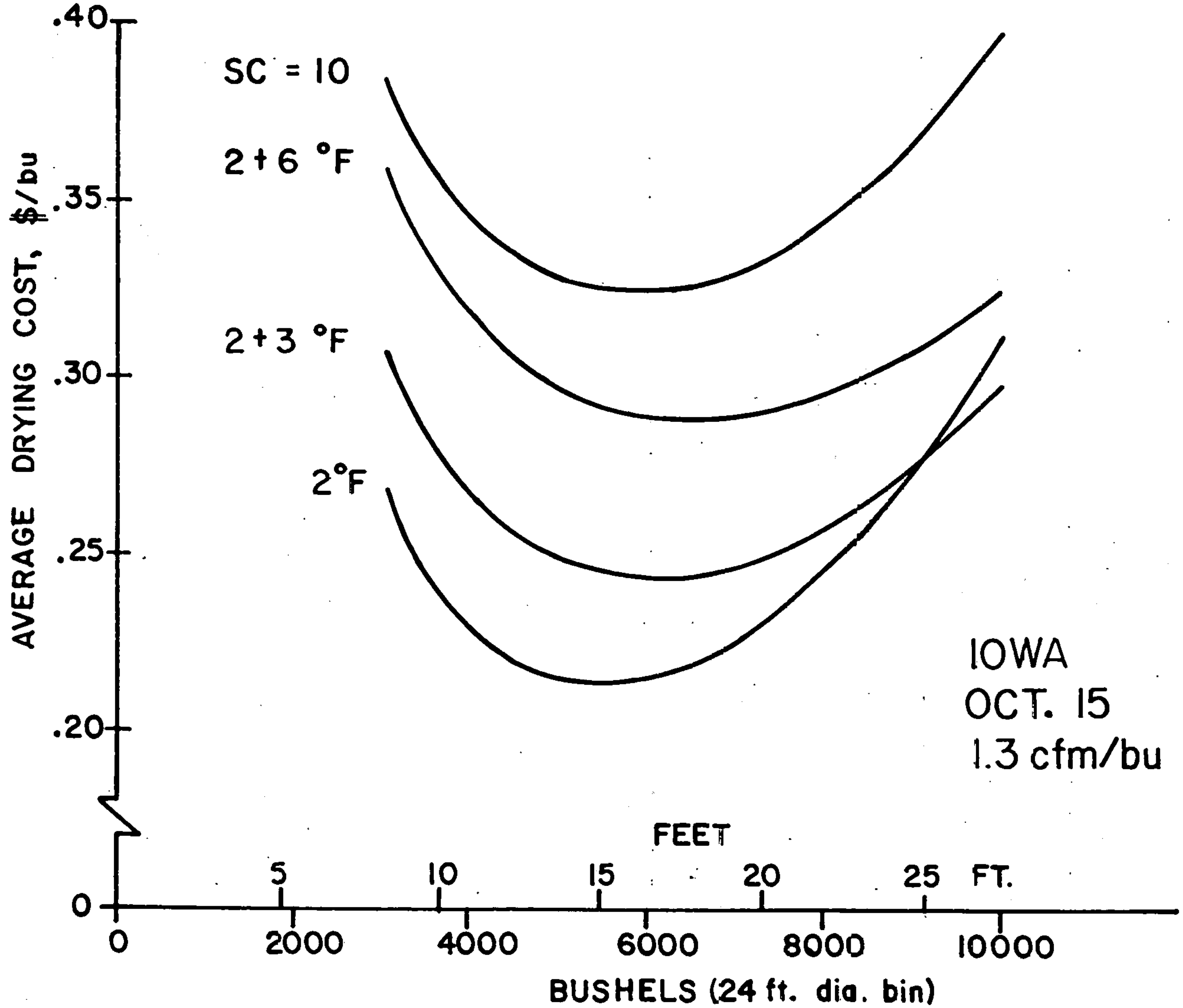

Figure 17. Effect of grain depth (in a 24 foot diameter bin) on the average drying cost for four low temperature grain drying systems.

Table 4. Effect of harvest date and various levels of supplemental heat (continuous and solar) on the average drying costs for Des Moines, Iowa conditions.

Average Cost (10 years),** ¢/bu
22% corn, 1.3 cfm/bu

Supplemental Heat Source	Temperature Rise*	Harvest Date 10/01	10/15	11/01
Ambient	$2^{o}F$	22.7	21.6	25.3
Continuous	$2 + 3^{o}F$	27.2	24.4	25.4
Continuous	$2 + 6^{o}F$	32.2	28.9	29.8
Solar	SC = 10	34.0	32.6	34.1

Average Cost (10 years),** ¢/bu
24% corn, 2.3 cfm/bu

Supplemental Heat Source	Temperature Rise*	Harvest Date 10/01	10/15	11/01
Ambient	$2^{o}F$	37.7	41.8	43.1
Continuous	$2 + 3^{o}F$	43.0	36.6	40.0
Continuous	$2 + 6^{o}F$	45.6	43.1	41.4
Solar	SC = 10	58.8	53.7	52.9

* All runs include a $2^{o}F$ temperature rise from pulling the air over the fan motor.

** All costs are based on the same costs and assumptions used for Figures 14, 15 and 16.

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ROLE OF THE COOPERATIVE EXTENSION SERVICE

Marvin D. Hall[1]

The Cooperative Extension Service is the link between the producer and the results of agricultural research. I think our role should be to instigate some applied research projects on the farm. Whenever possible these projects should involve full scale systems. Farmers have always been innovative, some more than others, and I see our role is to give as much engineering help as possible to people who are innovative and want to go ahead and do things a little bit different. We also need to give the same type of service to agriculture-related businesses, manufacturers, and related industries that want to do some research work in field testing or try new products or equipment. I also see our role as a backstop to producers or industry people where we may have a little expertise and can help on individual problems. For example, a building contractor may have a question on concrete specifications or on structural design. He should be able to pick up the telephone, call us, discuss the problem, and hopefully we can help him make a decision as it relates to a particular job. Or a farmer, or anyone else who has a particular question, should have access to extension specialists to help solve immediate as well as long range problems.

Over the years I've worked with many farmers and I've noticed a few characteristics. Some farmers are better than others, of course, just as some extension people are better than others. However, I can think of two characteristics of farmers who are good producers that characterize them more than anything else. The good farmer, as I would classify a good farmer, is trying to be number one, always looking for a better way to do something -- never quite satisfied. Regardless of what he does, he'd like to do it a little bit better. I think this is good, and I think we ought to promote this attitude as much as possible, not only in agriculture, but in everything else. The second characteristic I notice is that the successful farmer seems to pay a little more attention to detail, in fact, strict attention to detail. If I had to list two characteristics of the successful farm producer, those are the two: never quite satisfied and paying a little more attention to details than his neighbor does.

The application of solar energy to agriculture is being tried by the innovators -- the good producers. We must give them all the help we can. Their experiences will be very valuable in the development of practical, economical solar systems for agricultural production.

[1]Area Agricultural Engineer, Illinois Cooperative Extension Service, Region 3, Macomb, Illinois

EXPERIENCES WITH SOLAR GRAIN DRYING

Dan A. Ponder[1]

I grow about 450 acres of corn and 100 acres of soybeans. Prior to 1972 I dried the corn in two 4,400 bushel bins equipped with stirring machines and then transferred it to 25,000 bushels of permanent storage. I've run the operation by myself with some part time help. Four or five different people usually help us through the fall, at least for a short period of time. For me this ruled out a batch dryer with a continuous flow of heat that might need adjustment because I couldn't trust the temporary help to operate the dryer. However, it often meant long, tiring days for me. I'd be out in the combine all day and then come in at night and climb in and out of each of the drying bins three or four times to shovel wet corn. I'd use stirring machines and one of them might foul up a bit. I don't know if you've ever skinned-the-cat climbing up on one of those things -- that gets a little wearing, too. Also, I was climbing in and out of the bins checking grain moisture to determine when to transfer the corn to permanent storage. When you're transferring grain you can't combine, so I would try to transfer grain at 4:00 o'clock in the morning. I am reminded of what Bruce McKenzie, extension agricultural engineer at Purdue University said of this operation, "Each year you get one year older and two years tireder." Boy I was there! Just about that time I heard about low temperature grain drying -- a system of bin drying utilizing small temperature rises. I got hold of the University of Illinois agricultural engineers to help me set up some low temperature drying. This method of drying came as close to satisfying what I was after as I could find. I think it's the easiest, cheapest and simplest system that I've heard of. I know a lot of farmers who harvest 4,000 bushels in a day and store it in low temperature drying bins. Use of larger machines, more acreage, higher yields, etc., often leads to changes. Let me give you an idea of how much low temperature drying has helped me. Before I switched over I was just sore, stiff and tired; but since I switched in the past four years I haven't yelled at my wife or kicked my dog once.

Since this low temperature drying requires a very small amount of heat, maybe three or four degrees of extra heat in addition to two or three degrees from the fan, it has worked out very well for solar energy.

In the fall of 1974 I cooperated with the University engineers and tried an air inflated plastic bag solar energy collector to provide heat for one of my low temperature drying bins. We collected enough solar energy for low temperature drying of corn but the plastic bag collector had some problems. The plastic material is vulnerable to damage from high winds, snow, extremely cold temperatures, and animals, including small children who see it as a bouncy place to play. Watching over and repairing an air inflated plastic bag takes valuable time away from the busy harvest season.

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[1]Cash Grain Farmer, Tuscola, Illinois

In 1975 the University engineers suggested the construction of a more permanent solar collector on the side wall of one of my bins. The bin wall was painted black and a secondary wall of clear, corrugated fiberglass was built on the south side (Fig. 1). The 10 hp centrifugal drying fan was enclosed with fiberglass so that air was pulled over the black painted bin wall before it was forced into the plenum and up through the grain. The 27 ft diameter, 18 ft high bin provided about 800 sq ft of solar collector surface. Of course, because of the circular shape of the bin only about one half of this area is exposed to the sun at any given time. I feel that this collector did provide the necessary heat for low temperature drying of approximately 9,000 bushels in this bin during each of the years 1975 and 1976.

What about the future? It appears to me I will not need purchased energy, except electrical energy to power the fan, to dry corn in the bin now equipped with a solar collector. The collector should require a minimum of maintenance and I believe solar energy has a "bright" future for low temperature grain drying.

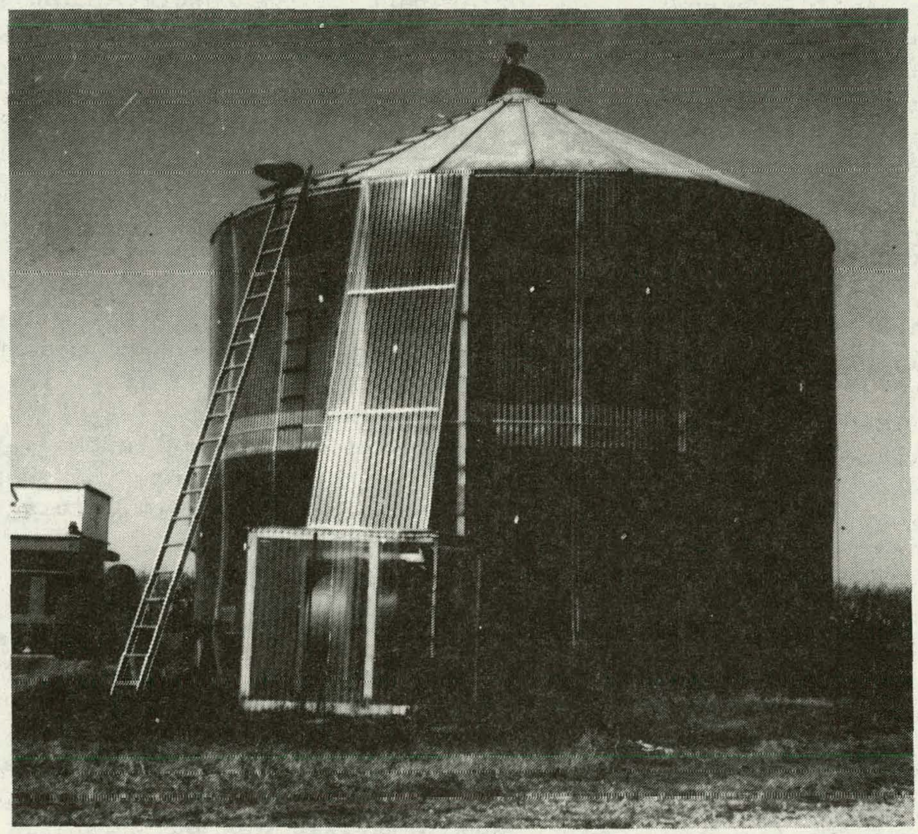

Fig. 1. Clear corrugated fiberglass placed around a black painted grain bin creates a covered-plate solar energy collector to provide heat for low temperature drying.

EXPERIENCES WITH SOLAR GRAIN DRYING AND SHOP HEATING

Randy Sims[1]

My father, uncle and I raise around 430 acres of corn, 200 acres of wheat, and about 300 to 350 acres of soybeans each year. We were in the process of planning a farm machine shed for additional machinery storage and asked Marvin Hall, area extension agricultural engineer, to help us locate the building. We are very fortunate in having Marvin Hall in our area and I want to give him credit for designing and helping us with the operation of our solar machine shed. After we decided we needed the machine shed, Marvin Hall suggested we put a plastic or fiberglass roof on it to collect solar energy for drying grain. We first thought he was kidding, but after we talked about it we were ready to go.

As the construction got started, Marvin also suggested we use solar heat to heat the shop we were building in one end of the machine shed. So we got a pump to circulate a water-antifreeze mixture through plastic pipe on the roof and through iron pipe embedded in the concrete floor of the shop. The idea being that the concrete slab would be a radiator. Sorry to report there doesn't seem to be a lot of heat in the concrete floor during the winter and we have a couple of problems to work out. I'm convinced the energy is there, and I'm convinced we can get it to work. One of the black plastic pipes that worked fine in the winter, crumbled during summer when it got over 200 F. We had a lot of leaks and had to replace the pipes. I don't believe we've got enough pipes back up in the roof to generate sufficient heat for the concrete floor.

BUILDING CONSTRUCTION

The machine shed is basically a pole building with an eave height of 14 ft. Door sizes and locations are designed to accomodate the needs of modern farm equipment. The building dimensions are 50 ft by 100 ft (Fig. 1). One end of the building is partitioned to provide a heated shop area 32 ft by 50 ft with an overhead door to the outside and sliding doors in the partition wall. The inside doors allow machinery to be moved into the shop area without going outside in bad weather. An office, chemical storage room, toilet and sink are located in one corner of the shop.

Heat for the shop area is provided by 1400 ft of 3/4 inch black plastic pipe on the south side of the machine shed roof. This pipe is connected to 1/2 inch black iron pipe located 2 ft on centers in the shop floor. The original design called for two pumps to circulate water through the pipe system. One pump to circulate water through the roof pipes and water heater, and a second pump to circulate water through the floor pipes and the water heater. There is also a fan in the shop wall to bring in fresh air and heat when it is needed and is available (Figs. 2 and 3). The controls for the water pumps and the shop fan are described in Fig. 4.

[1] Manager, Sims' Farms, Liberty, Illinois

SOLAR COLLECTOR

Air is pulled the full length of the building beneath the fiberglass roofing from the west to the east end where it is collected in a cross-duct and pulled down the wall to a 3 ft diameter steel culvert that carries it to the grain bins. The duct should be sized to keep air velocity below 1,000 ft/min to avoid excessive pressure loss which would reduce the output of the fan. Systems should be planned so that part of the air to the drying fan can be bled into the fan at the fan if excessive negative pressures are encountered.

The building is still considered experimental in many ways. The life expectancy of fiberglass roofing used as a solar collector is still unknown; however, it looks very good to date. We have found that the material used behind the collector needs to be able to withstand temperatures exceeding 200 F and still maintain strength and shape. The dual pump system did not function properly and the water heater element burned out during the winter. After one pump was disconnected and floor pipes hooked directly to roof pipes, the system functioned much better. Further study is necessary on a closed loop-dual pump system if constant floor temperature is required.

SOLAR DRYING

The two 3,300 bushel bins were filled in the fall of 1975 and dried to safe storage levels. There was no heat used other than the solar roof of the machine shed. The drying fan delivered approximately 7,000 cfm and the temperature gain over outside air during mid-day hours varied from a low of 5 F to a high of 30 F, with an average temperature rise from 10 to 20 F at mid-day. With a 5 F temperature rise the approximate solar heat gain was 37,800 Btu/hr and 226,800 Btu/hr with a 30 F temperature rise. For the entire roof of about 5,200 sq ft this computes to a solar heat gain from approximately 7 Btu/hr sq ft to 42 Btu/hr sq ft. Assuming an average temperature rise of 20 F, the average heat gain would be 151,200 Btu/hr or 29 Btu/hr sq ft.

My estimated cost of solar drying 6,500 bushels of corn in the fall of 1975 was 1.2¢/bu based on the operation of a 5 hp fan for 21 days. The cost of drying using LP gas and a 10 hp fan on a bin equipped with a stirring machine was 4¢/bu. These cost figures do not include depreciation, insurance, etc., but relate only to operating costs.

The quality of the grain coming out of our solar drying system is excellent compared to our faster, gas heated drying system. The solar dried corn does not break up during handling; and, although I do not have documented facts on quality difference, I sure do like to feed the solar dried corn. It's cleaner, easier to work with, and I think it should be more palatable to the livestock.

SHOP HEATING

To heat the shop with solar heated air we installed a variable speed fan in the wall duct to pull air through the roof collector. The variable speed allows us to slow down the fan to prevent drafts if the incoming air is cold but still a few degrees above the shop temperature. As the solar collector creates higher temperature rises, we can increase the airflow. It's not uncommon to get 50 to 60 F rises on sunny winter days. The fan to pull solar heated air from the roof really works to warm the shop.

SUMMARY

At this time it looks very promising and practical to adapt old buildings or to incorporate solar energy collectors into new construction to collect solar energy to dry grain. Heating a shop is a good fringe benefit and will help justify the cost of the collector (Table 1).

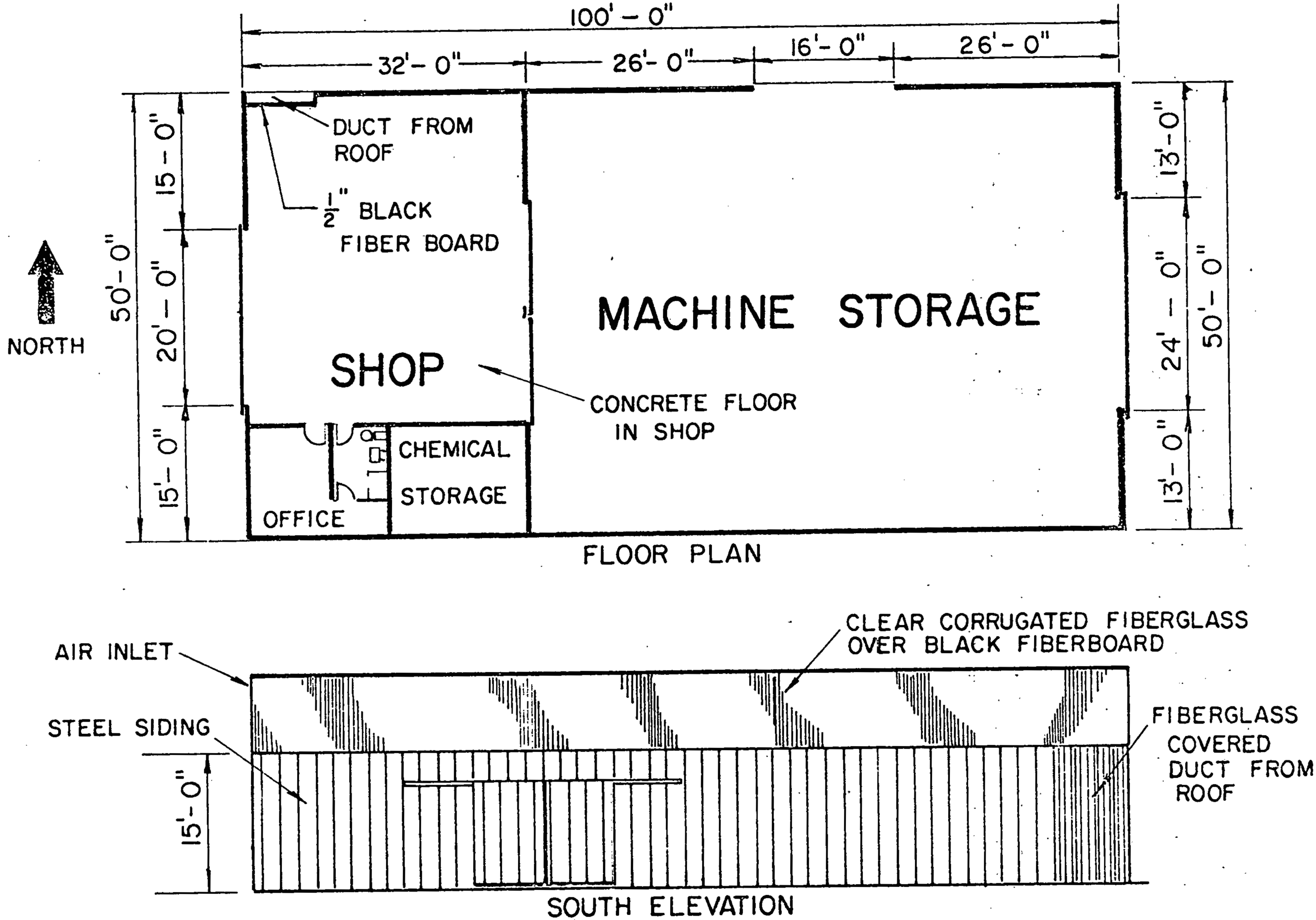

Fig. 1. Dimensions of a machine storage building and repair shop with clear fiberglass roof to create a solar energy collector to dry grain and heat the shop.

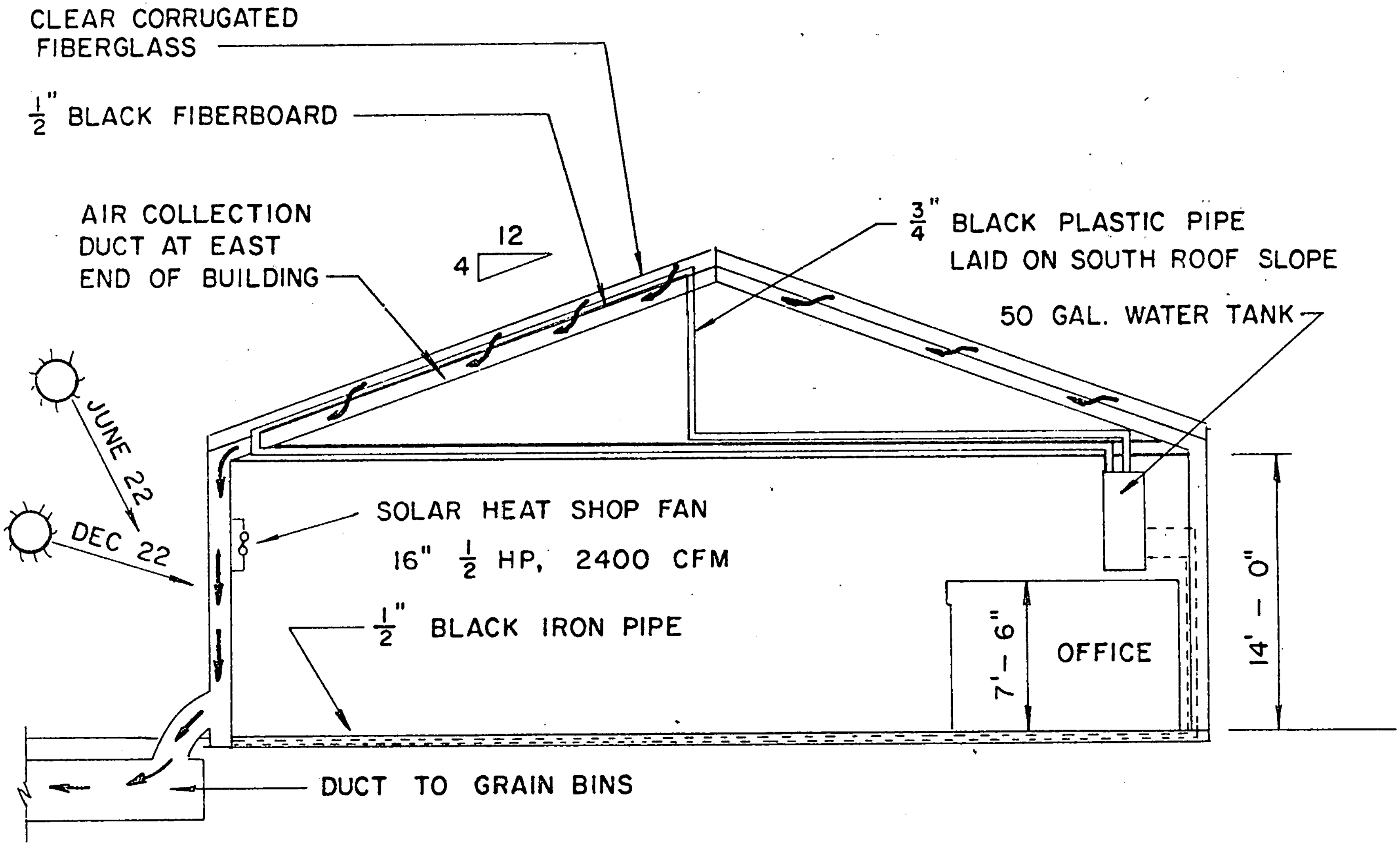

Fig. 2. Cross section of a machine storage building with solar collector incorporated into the roof.

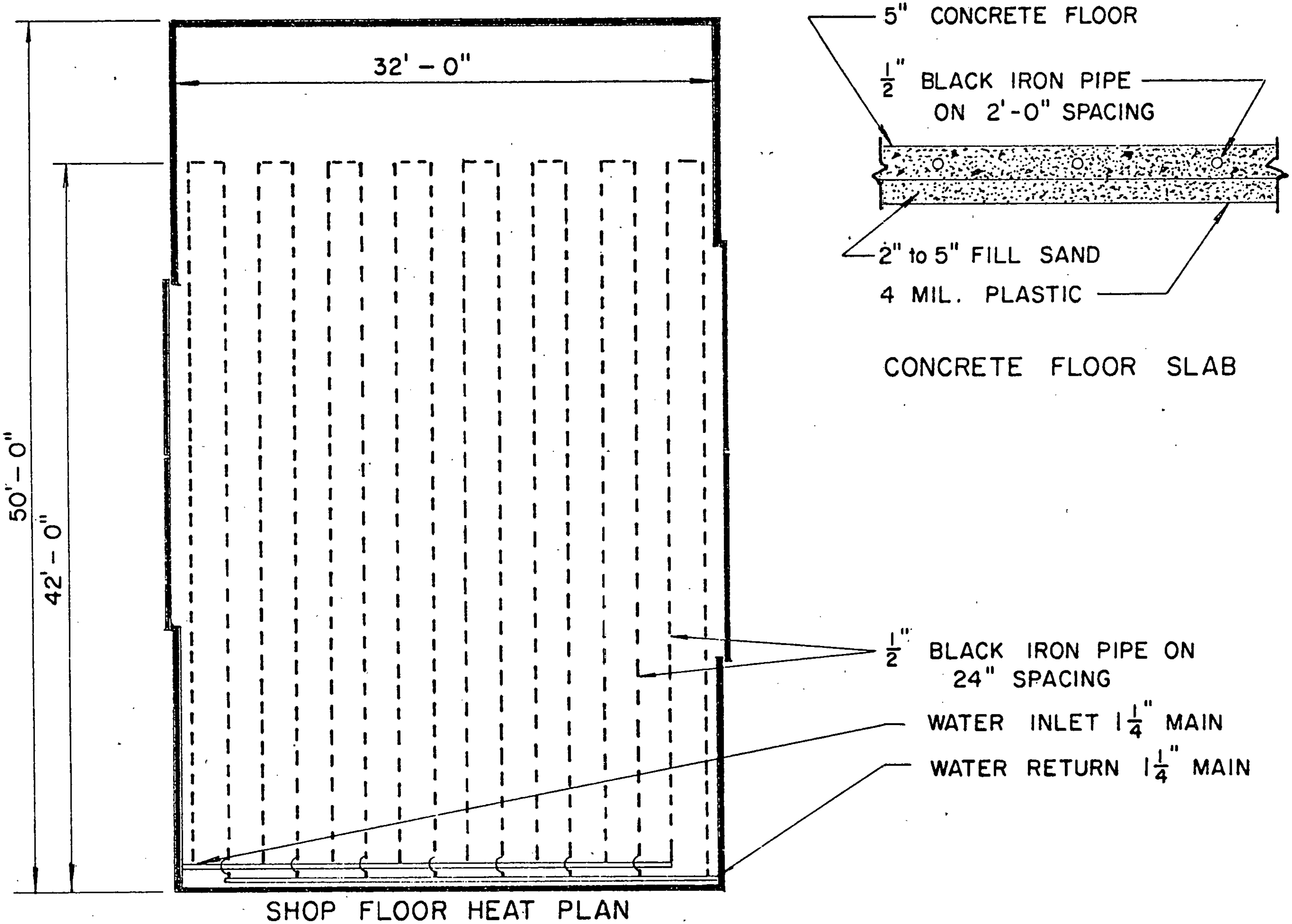

Fig. 3. Layout of iron pipes embedded in concrete shop floor for circulating a solar heated liquid to warm the floor.

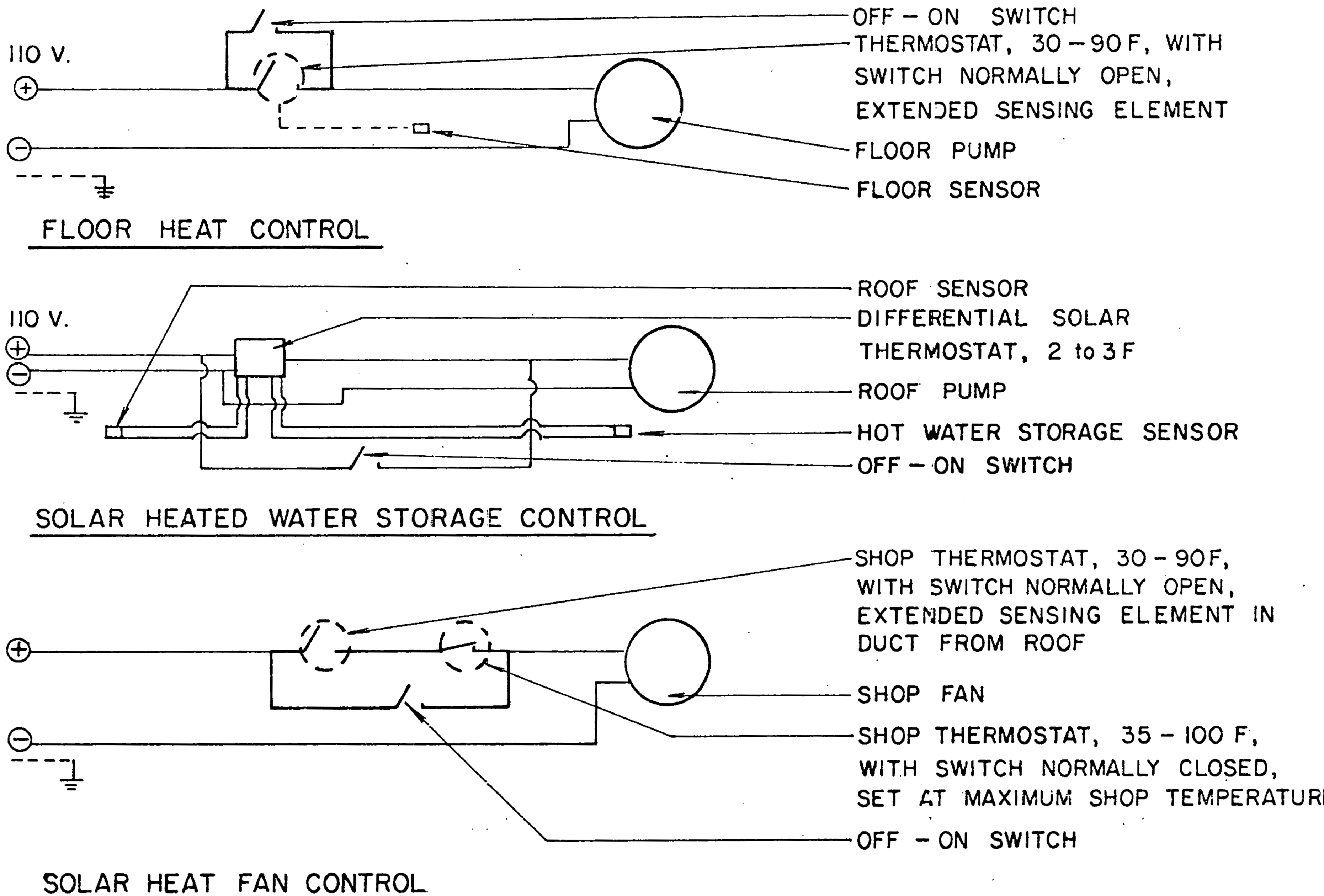

Fig. 4. Controls for pumps and shop fan installed in a machine storage building having a solar collector roof.

Table 1. Cost of Incorporating Approximately 5,200 Sq Ft of Covered Plate Solar Energy Collector Into the Roof of a 50 x 100 Ft Machine Shed on the Sims Farm in 1975

Insulation Board		$478.80
Pipe, Black Iron and Plastic		759.41
Corrugated Pipe and Elbow		583.50
Concrete for Drop Boxes		256.54
Sand		112.00
Fan		70.00
Hot Water Heater and Pipe Fittings		175.25
Barrels and Sheet Metal		45.74
Pumps, Controls, and Wiring (Estimated)		450.00
Additional Labor Costs (Estimated)		2500.00
	Subtotal	$5431.24
Cost of Plastic Roof, Nails, Washers, and Caulking (covered approximately 5,200 sq ft of roof, plus 112 sq ft of side-wall with approximately 800 sq ft left over.)		$2674.30
	Total	$8105.54

EXPERIENCES WITH SOLAR GRAIN DRYING AND LIVESTOCK SHELTER HEATING

Darrell Lasswell[1]

My farm lies about 35 miles northeast of Peroia, Illinois in Marshall county in north central Illinois. In 1976 we started a complete new farmstead, which included a grain handling center and a farrow to finish livestock facility. I would like to acknowledge Marvin Hall with the Cooperative Extension Service as the engineer who helped us plan the farmstead and we are using his plans for the swine facility.

CONSTRUCTION

The swine building is 44 ft wide and 184 ft long with the dark green metal roof used as a bare plate solar energy collector. There are 32 farrowing crates in the farrowing section and 20 pens in the nursery section of the building each capable of holding two to three sows and litters. There is a concrete slat that has a hot water pipe embedded in it for supplemental heat in the farrowing and nursery sections. The finishing section is approximately 100 ft long with 24 finishing pens capable of holding around 25 market weight hogs. We sometimes refer to such a building as a "womb to tomb" building since baby pigs are born at one end of the building and go to their tomb (to market for slaughter) out the other end. A complete feed handling and processing system allows me to mix my own vitamins and antibiotics together with other feed grains through an automatic grinding mill. Feed is purchased in 20 ton loads and handled through an elevator leg and other conveyors.

SOLAR VENTILATION SYSTEM

The ventilation air for the building is pulled along the underneath side of the dark colored roof before it is introduced into the building in an attempt to obtain some solar heating of the air. The solar air chamber was created by laying 8/10 inch urethane foam insulation boards on the top of 2 x 4 inch purlins on edge running the length of the building. The urethane boards have a vinyl coating on one side and aluminum foil on the other side. On top of the insulation boards 2 x 2 inch wood members were placed to support the dark colored metal roof sheets. When the ventilating fans call for air, air is pulled in under the roof overhang, up underneath the dark colored steel and above the insulation. The solar heated air is collected in a central chamber and distributed from the center of the building by 3 ft x 4 ft ducts that run from the center of the building. Air is blown into the area where the animals are, down through the floor slats, into the eight foot manure pit, and exits through vents in the side of the concrete wall of the building.

[1] Grain and Swine Producer, Washburn, Illinois

SOLAR DRYING SYSTEM

To collect solar energy for drying grain, air moved by the drying fans is channeled through the entire length of the duct in the building. At one end of the building the air is ducted down into the ground where it enters a 3 ft diameter culvert. The underground culvert extends to two 36 ft diameter grain drying bins -- a total length of 110 ft. At each bin a small house, enclosing a 20 hp centrifugal fan sits over a slot in the culvert. A sliding door in the side of each house provides a means for regulating airflow through the solar roof of the swine building. With both slide doors closed, supposedly all the air moved by the two fans, approximately 36,000 cfm, would be moved through the solar air chamber in the roof of the building.

We put the first grain in one of the 36 ft bins the first of October, about 3,000 bushels at 22% moisture content. The first thing that happened was the centrifugal fan collapsed the ventilation ducts. This was not too damaging since we could get inside the ducts and push them back into place with some plywood strips. The air was then adjusted to get more air from the outside into the fan and less through the building roof. The fan ran approximately 8 days during very good weather, the last good weather we had in 1976, as far as grain drying was concerned. Since I was very busy trying to complete the electrical wiring in the building, the feed handling system, getting the grain in and out, I have no data on the drying of this 3,000 bushels of corn. In eight days the corn was dried to 15.5% moisture. The fan was shut off and it wasn't until the latter part of October that we got back to harvesting corn on this farm and putting it into the drying bins. At this time we put 9,000 bushels of 22% moisture corn on top of the previously dried 3,000 bushels and started the fan. Everything seemed to be working well for several days and we were getting a 5 to 10F degree temperature rise above the outside air, varying with the time of day and amount of sunshine.

About the 1st of November we put some grain in the second bin and started the fan then noticed we were pulling some air through the swine building in a reverse direction in relation to the regular ventilation system. I take full responsibility for not completing some of the carpentry work inside the ventilation ducts to prevent this reverse flow of air through the vents along the side of the building. This reverse flow of cool or cold air presents problems for our hogs. We had about 600 head in the finishing end at the time and since the hogs are important -- that's what the building was built for -- we stopped the solar drying of grain.

I have been up into the ventilation ducts, inspected the problems and be next harvesting season will have everything in working order. I am very optimistic about solar grain drying using the roof of the swine building as a collector. I am even more optimistic about drying grain than I am about heating the hog building itself.

POTENTIAL APPLICATION OF SOLAR ENERGY TO COMBINATION[1/][2/] (HIGH-LOW) TEMPERATURE DRYING

R. Vance Morey and Harold A. Cloud[3/]

INTRODUCTION

Three major concerns in drying are energy use, drying capacity and grain quality. Energy use in drying is currently receiving much attention because of the national concern with energy supplies and availability. The emphasis is on making more efficient use of energy for drying as well as reducing the current reliance on high-grade fuels such as propane and natural gas. A second concern is drying capacity or performance. Although this concern has been listed second it is probably the first priority in designing or developing drying systems since a system must first meet the demands on capacity and performance if it is to be successful. The need to obtain increased drying capacity has influenced the development of high-temperature dryers which in many cases are less efficient than other systems. The third concern is grain quality which has always been a factor for consideration in drying system design but has not always received high priority because of the lack of economic incentives to develop improved quality. However, continuing concern with the susceptibility to breakage of grain dried in high-temperature dryers makes this a factor to be considered.

Combination high-temperature, low-temperature drying offers potential for answering the above concerns (Cloud et al., 2). The purpose of this paper is to present information on energy use for combination drying, and to evaluate the reduction in energy required in the low-temperature drying phase by using supplemental solar heat in addition to ambient air. These evaluations are made for three locations: St. Cloud, Minnesota; Des Moines, Iowa; and Indianapolis, Indiana.

1/ Journal Series Paper No. 9802 of the Minnesota Agricultural Experiment Station.

2/ Research reported in this paper was partially supported by a grant from the Agricultural Research Service, USDA and the Energy Research and Development Agency (ERDA).

3/ Associate Professor, and Professor and Extension Engineer, respectively, University of Minnesota, St. Paul, Minnesota.

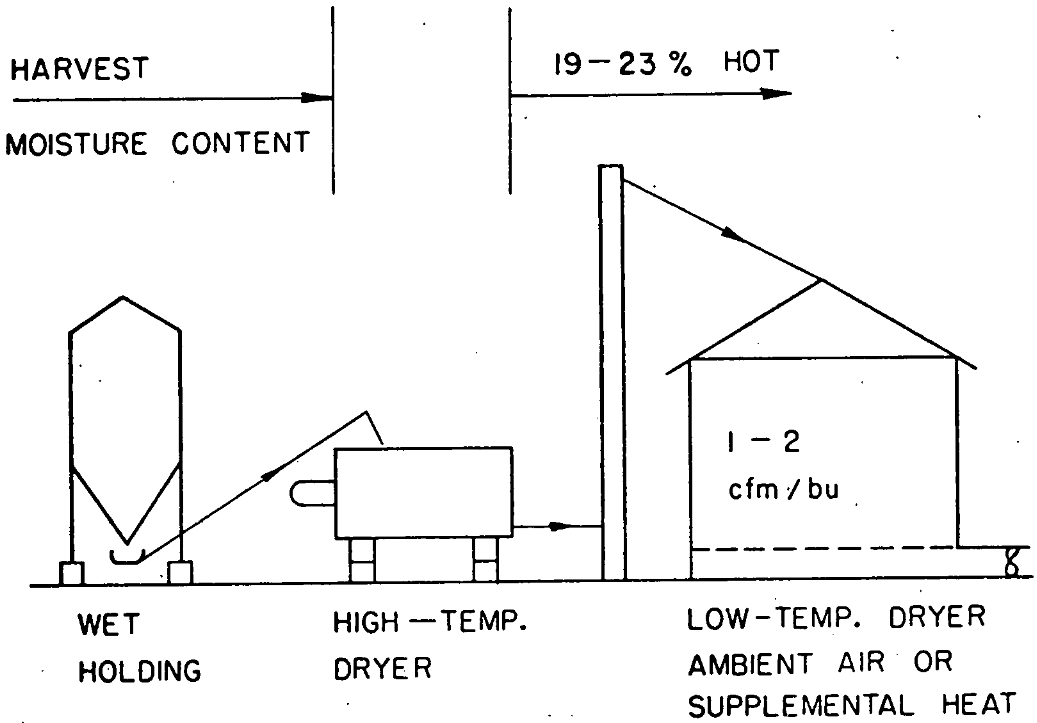

Figure 1. Schematic diagram of combination drying system.

DESCRIPTION OF COMBINATION DRYING SYSTEM

In a combination system, grain is partially dried in a high-temperature (160-240°F) dryer which uses propane or natural gas fuel for heat energy. Following the initial phase grain is discharged hot to the drying bin, slowly cooled to efficiently recover sensible heat in the corn and then dried with ambient air or low-temperature air (air heated to 2-7°F). Low-temperature drying in the low moisture range takes advantage of the drying capacity in the ambient air and is, therefore, generally efficient. A schematic diagram of the combination method is shown in Figure 1.

At moisture contents above 22-24% w.b., decreased allowed storage times dictate shorter drying times which reduce the performance and energy efficiency of low-temperature systems. Allowable storage times for shelled corn as a function of grain moisture content and grain temperature are indicated in Table 1. As the moisture content increases, allowable storage time significantly decreases. Temperature also has a significant effect on allowable storage time as indicated by the data. If low-temperature drying can take place at reduced temperatures, allowable storage time is significantly increased.

Based on the information on allowable storage time and estimated drying times for average weather conditions, recommendations for minimum airflow rates for low-temperature drying have been developed. These recommendations include: 1 - 1 1/2 cfm per bushel for 22% moisture content corn;

Table 1. Allowable storage time for shelled corn.1/

Corn Temp. °F	Moisture Content 15%	18%	20%	22%	24%	26%	28%
35	1174	242	120	71	48	35	28
40	879	181	90	53	36	26	21
50	492	101	50	30	20	15	12
60	275	57	28	17	11	8	6

1/ Based on 0.5% dry matter decomposition (Steel et al., 9).

2-3 cfm per bushel for 24% moisture content corn and 3-4 cfm per bushel for 26% moisture content corn. These minimum airflow rates depend on a number of conditions including location. Minimum airflow rates will be discussed in more detail later in the paper.

As airflow rates increase, fan horsepower requirements increase significantly. Estimated fan horsepower requirements for a 10,000 bushel bin at various airflow rates and depths of fill are illustrated in Table 2. These data indicate that depth of fill must be severely restricted at higher airflow rates to maintain reasonable levels of fan horsepower. Combination drying guarantees moisture contents of 22% or less into the bin which the table indicates can be handled at reasonable depths of fill with a reasonable fan horsepower.

By reducing the amount of moisture removed in the high-temperature dryer, energy requirements supplied by propane or natural gas are significantly reduced. In addition moisture removal in the higher moisture content range is more efficient. Since grain is discharged from a high-temperature dryer at higher moisture contents, capacity of the dryer is significantly increased, often by a factor of 3-4 times. Grain is discharged hot from the high-temperature dryer to provide an additional increase in high-temperature capacity and some additional efficiency in moisture removal during cooling. Experience has shown that grain can be cooled, dried, and stored in one bin without condensation problems if the drying fan is turned on as soon as the grain is emptied into the bin (Morey, et al., 7).

Using high-temperature drying at the upper moisture content levels and then completing drying with low-temperature methods leads to improved grain quality. Gustafson et al. (3) found that high-temperature drying to approximately 22% w.b. followed by cooling and low-temperature drying to the final moisture content greatly reduced susceptibility to breakage compared to conventional high-temperature drying to 15 1/2% moisture content. Therefore, it appears that the desirable grain quality characteristics obtained with low-temperature drying can be obtained using combination methods if low-temperature drying is used below 21-22% moisture content.

Table 2. Brake horsepower per 10,000 bushels and total temperature rise data for several airflow and depth combinations.

	Depth, ft											
	8		12		16		20		24		28	
cfm/bu	hp 1/	Temp. 2/ Rise °F	hp 1/	Temp. 2/ Rise °F	hp 1/	Temp. 2/ Rise °F	hp 1/	Temp. 2/ Rise °F	hp 1/	Temp. 2/ Rise °F	hp 1/	Temp. 2/ Rise °F
0.5	0.30	0.16	0.74	0.40	1.44	0.78	2.40	1.30	3.67	1.99	5.29	2.86
0.75	0.74	0.27	1.87	0.67	3.67	1.32	6.24	2.25	9.36	3.40	14.23	5.13
1.0	1.44	0.40	3.67	0.99	7.31	1.98	12.6	3.41	19.67	5.32	29.12	7.87
1.25	2.40	0.52	6.24	1.35	12.61	2.73	22.06	4.77	34.5	7.46	--	--
1.50	3.67	0.66	9.64	1.74	19.67	3.55	34.51	6.22	--	--	--	--
2.0	7.31	0.99	19.67	2.66	40.34	5.46	71.86	9.72	--	--	--	--
3.0	19.67	1.77	54.46	4.91	115.0	10.40	--	--	--	--	--	--

1/ Brake horsepower per 10,000 bushels based on ASAE D272(1) x 1.5 and a fan efficiency of 50%.

2/ Assuming an 85% efficiency for the fan motor (878 watts per brake hp). 57.5% of this total appears as a temperature rise in the plenum.

The potential advantages for combination drying can be summarized as follows:

1. Reduction in the amount of propane or natural gas required for heat energy in the high-temperature dryer.

2. Reduction in total energy requirements (heat energy plus electrical). Although electrical energy requirements are increased, most of this use comes in the Fall (October and November) and in the Spring (March and April) which are between the seasonal air conditioning and heating peaks in the corn belt.

3. Increased drying capacity for the high-temperature dryer which would allow for off-peak operation or a smaller dryer to maintain the same total capacity.

4. Improved grain quality due to slow cooling and low-temperature drying at the lower grain moisture contents.

5. Flexible system that can dry high-moisture content grain under adverse weather conditions without delaying harvest.

6. Concept can be implemented in the near term using existing technology (i.e., equipment required is already being utilized in other types of drying systems and much of it may already be in place in many farm drying systems).

A major question that remains is the importance of supplemental heat in low-temperature drying. In most systems the energy supplied to the drying fan and motor is utilized for heating the drying air. In most cases this amounts to a 2°F temperature rise or more. The effect of an additional 2-4°F of supplemental heat supplied either by constant source electric or propane, or by solar energy is questionable. The addition of supplemental solar heat will lead to a lower final moisture content in most cases. In some cases this results in over-drying of the grain which is not desirable. In other cases the desired final moisture content can be obtained with ambient air plus energy from the fan by drying in the Spring when weather conditions provide lower equilibrium moisture contents.

Another question is the effect of supplemental heat, constant source or solar, on the minimum airflow required to dry within the allowable storage time. Pierce and Thompson (8) have shown that in most locations supplemental heat does not significantly reduce the minimum airflow requirement for drying. Fan energy requirements for the low-temperature drying appear to be somewhat reduced by supplemental solar energy; however, the amount varies depending on the location.

Table 3. Energy data used in estimating high-temperature dryer energy requirements.1/

Discharge Moisture Content, % w.b.	Btu/lb of water	
	Heat (Propane or nat. gas)	Electric
15 1/2	2,410	40
20	1,800	25
22	1,620	25

1/ Based on experimental (Morey et al., 6) and simulation (Morey et al., 4) results.

ANALYSIS OF COMBINATION DRYING PERFORMANCE

Energy use estimates for the high-temperature dryer are based on experimental and simulation results from a crossflow dryer operating in the 200 to 220°F range at 75 cfm/bu airflow rate (Table 3). High-temperature dryer performance is assumed to be the same for all locations.

Low-temperature comparisons are based on simulation results from a model developed by Thompson (10) and modified by Morey et al. (6). The model predicts moisture changes and dry matter decomposition (from which allowable storage time can be determined) in response to changes in weather data. The model was validated with data from two field scale drying tests, one with supplemental solar heat. The validation results showed that the model was suitable for predicting grain moisture content changes (Morey et al., 6). The dry matter decomposition component of the model could not be directly validated with the field data. However, the model predicted that the grain in the top of each of the bins used in the field tests approached the 0.5% dry matter decomposition which is associated with the maximum allowable storage time. Visual inspection of the grain from the tops of these bins indicated that the allowable storage time had been exhausted. Although not a complete validation, at least this information indicates that the model adequately predicted deterioration levels in this case.

Daily average dry bulb and wet bulb temperatures for each location are used in simulating low-temperature drying performance. Total daily solar radiation incident on a horizontal surface is used to predict energy provided by solar collectors. Sixteen, ten and fourteen years of data are available for St. Cloud, Des Moines and Indianapolis, respectively.

Operating policies and assumptions related to the low-temperature drying are listed below:

1. Low-temperature drying starts on October 15 at a specified moisture content after the grain has been cooled.

2. Drying is simulated until the average grain moisture content in the bin is less than 14% and the top layer is less than 15 1/2%. Dry matter decomposition comparisons are based on reaching this final level of moisture. The top layer is defined as the grain in the upper 10% of the bin in all comparisons that follow.

3. The fan is operated continuously until the final moisture content is reached or the fan is shut-off at the end of the Fall season. If drying is not completed in the Fall the fan is restarted on March 16 and operated continuously until the final moisture content is reached. Two conditions can shut off the fan in the Fall:

   a) after December 1 when the top layer of grain is less than 19% w.b. and the grain temperature is less than 25°F, or

   b) after January 1 when the top layer is less than 25°F independent of moisture content.

4. Energy comparisons are based on the hours of operation until the first occurrence of an average moisture content less than 15.5% with the top less than 18%.

5. A total temperature rise of 2°F is assumed to be supplied by the drying fan for all airflow rates. The corresponding grain depth and fan power requirements can be found from Table 2 for the specified airflow rate and 2°F temperature rise. Based on a combined fan and motor efficiency of 42.5%, 1.15 degrees of the temperature rise is added in the plenum and the remaining 0.85 degrees which is a result of friction energy in the grain is divided uniformly and added to the air in each layer.

6. Supplemental solar heat is added in some applications. The temperature rise resulting from solar radiation is specified in terms of a solar coefficient as defined by Pierce and Thompson (8).

Simulated dry matter decomposition results using the 16 years of weather data for St. Cloud are indicated in Figure 2 for the case of October 15 starting date, 1 cfm/bu airflow rate, 22% w.b. initial moisture content, 2°F from the fan and no supplemental heat. The three best and three worst years based on dry matter decomposition of the top layer are presented. In two of those years dry matter decomposition exceeded 0.5% in the top layer by the final stopping date.

For each year it can be seen that the greatest rate of dry matter decomposition occurs in the Fall. In all cases the rate is greater during the last half of October than it is in November. This is due to the higher temperatures occurring in October. Fall shutdown dates are indicated for each year. At this time the grain is below 25°F. Deterioration

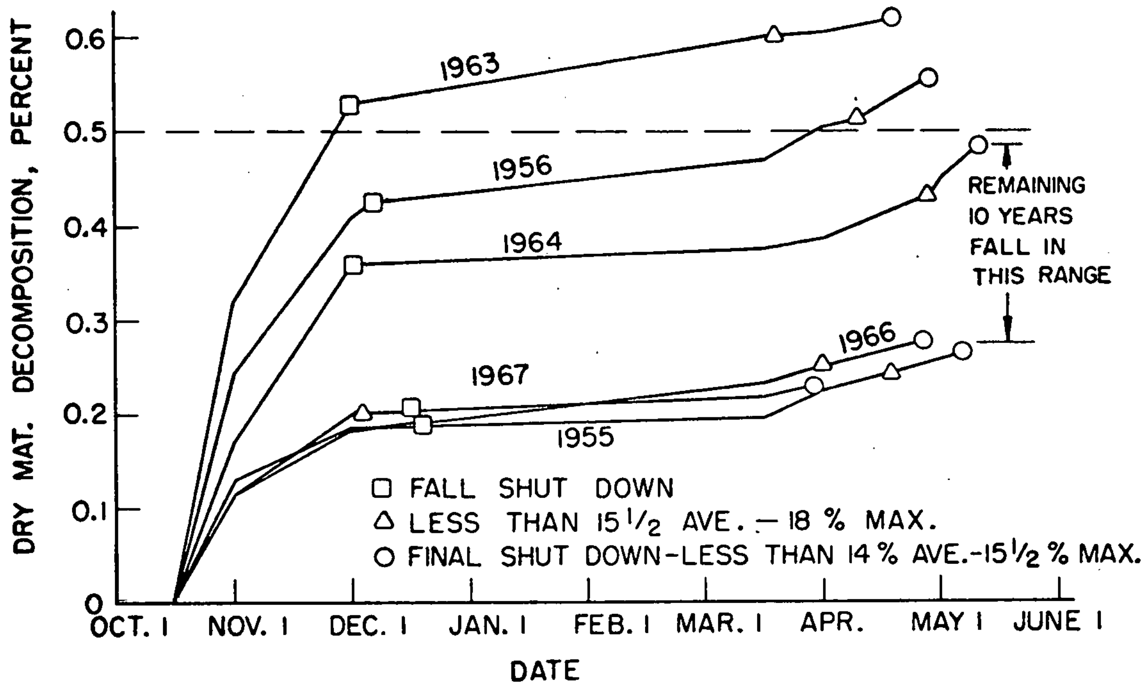

Figure 2. Top layer dry matter decomposition for three best and three worst years out of 16 (1 cfm/bu, 22% initial M.C., Oct. 15 start, no supplemental heat, $2^{o}F$ total temperature rise from fan, St. Cloud, MN).

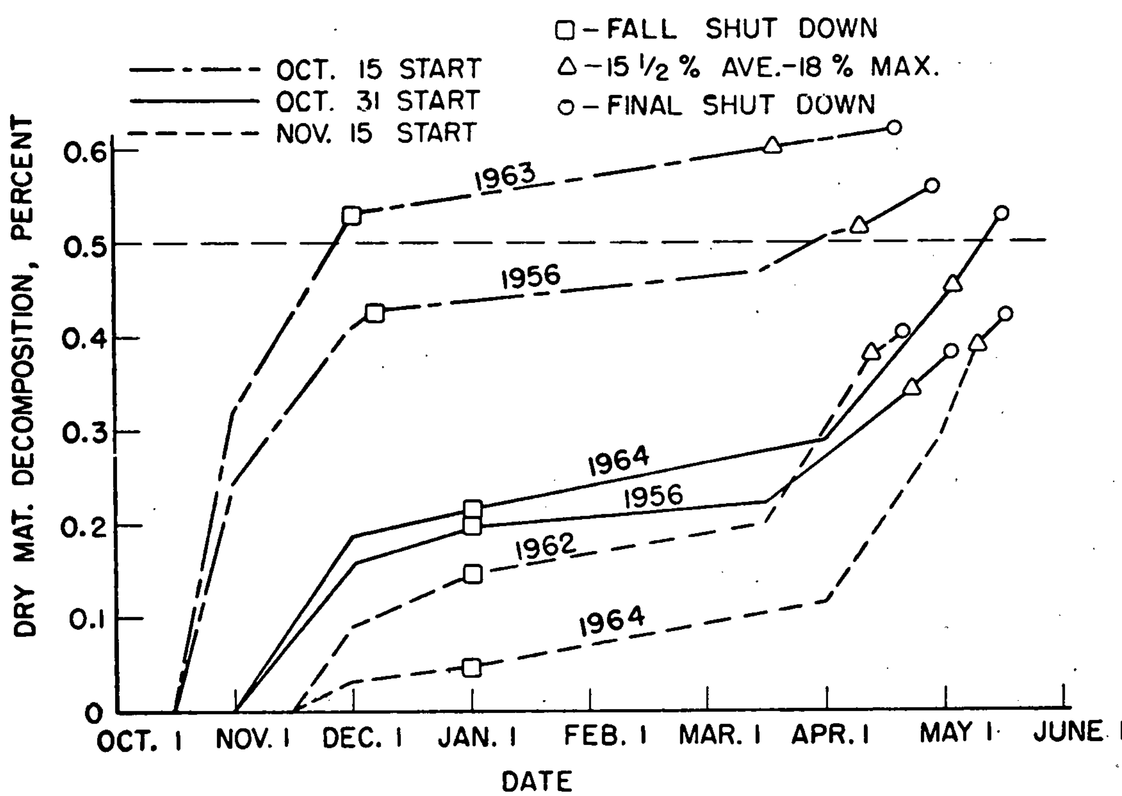

Figure 3. Top layer dry matter decomposition for two worst years out of 16 for three starting dates (1 cfm/bu, 22% initial M.C., no supplemental heat, $2^{o}F$ total temperature rise from fan, St. Cloud, MN).

continues at a low rate depending on the moisture content. At startup on March 16 drying continues and the rate of deterioration increases somewhat due to the higher grain temperatures.

Dry matter decomposition results for systems with no supplemental heat and three starting dates are compared in Figure 3. The two worst years for each starting date are plotted. These results show that for the October 15 start most of the dry matter decomposition occurs in the Fall. For October 31 and November 15 starting dates, half or more of the dry matter decomposition occurs in the Winter and following Spring. By October 31 ambient temperatures are low enough so that the rate of dry matter decomposition is greatly reduced for the remainder of the Fall.

Dry matter decomposition results for the October 15 starting date with no heat and solar coefficients of 10 and 20 are plotted for the two worst years in Figure 4. A solar coefficient of 10 corresponds to 0.18 sq.ft./bu of horizontal collector area at an efficiency of 40% and a 1 cfm/bu airflow rate. For these same conditions a solar coefficient of 20 corresponds to 0.36 sq.ft./bu of horizontal collector area. The average temperature rise due to supplemental heat varies each year because of the variation in the amount of solar radiation. The results show that supplemental solar heat causes slightly greater dry matter decomposition in the Fall than no heat. However, the additional drying time required in the Spring for the no heat system causes the dry matter decomposition to surpass that of the solar heated systems. In both years the final differences between the no heat and supplemental solar heated cases are small.

Preceding results have illustrated the performance of low-temperature systems under various operating conditions for St. Cloud. To compare energy requirements for combination drying systems at different locations, it is necessary to compare the low-temperature component on an equal dry matter decomposition basis. In the comparisons that follow, minimum airflows will be selected for low-temperature drying which produce 0.5% dry matter decompositions for the top layer in the worst or second year. The time required to accumulate 0.5% dry matter decomposition is considered to be the allowable safe storage time.

The relationship between airflow rate and moisture content for the worst and second worst year for St. Cloud is shown in Figure 5. At the higher moisture contents the minimum airflows based on the second worst year are substantially less than required to meet the allowable storage criteria in the worst year. At the lower moisture contents the difference in airflows based on the two criteria is much less. The effect of supplemental solar heat on the minimum airflow requirements is shown at the lower airflow range. These results indicate that supplemental heat reduces the minimum airflow requirements by approximately 10% at these airflow levels.

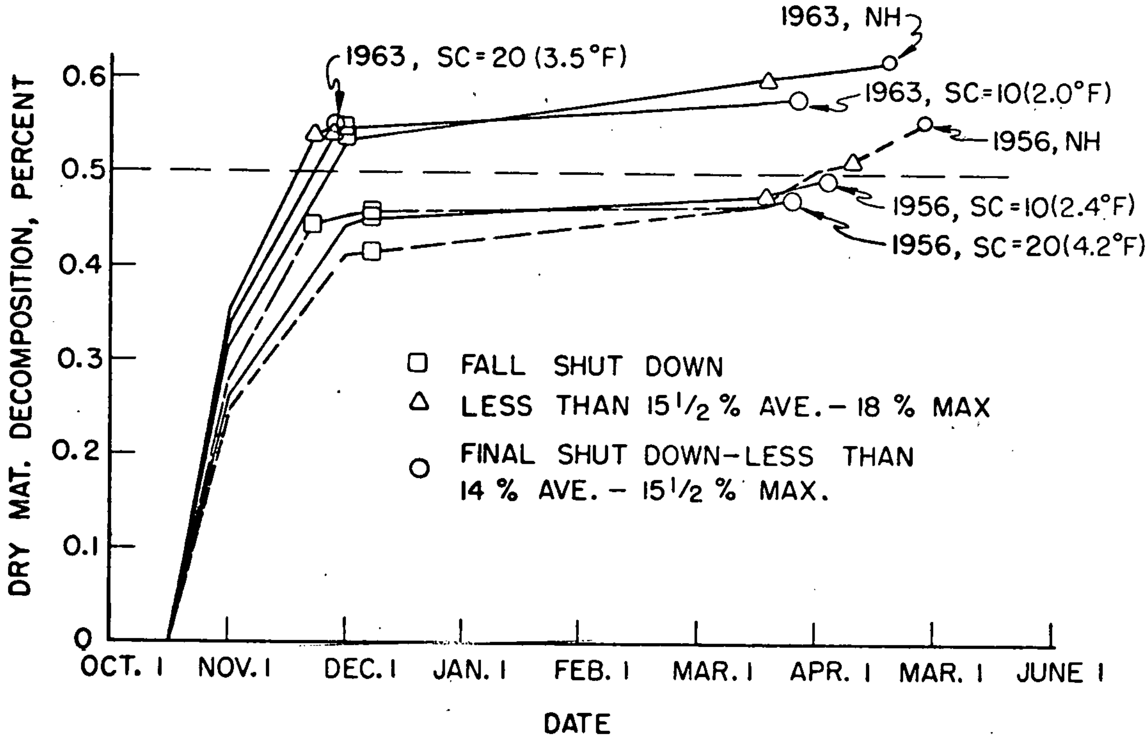

Figure 4. Top layer dry matter decomposition for two worst years out of 16 for no heat, SC=10 and SC=20 (1 cfm/bu, 22% initial M. C., Oct. 15 start, 2°F total temperature rise from fan, St. Cloud, MN).

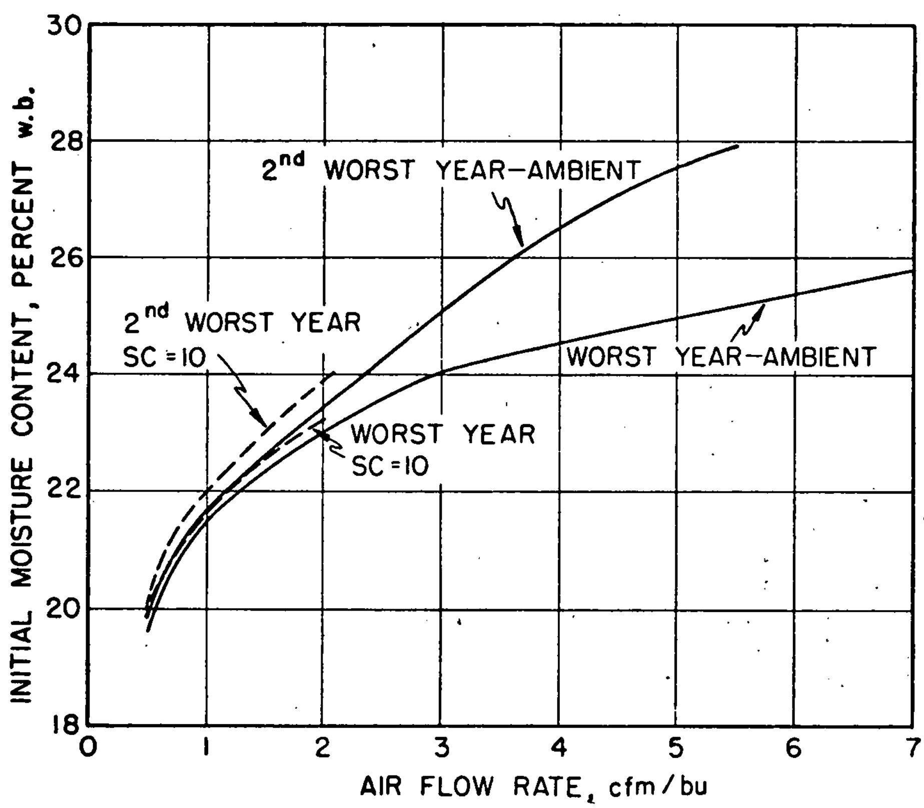

Figure 5. Top layer dry matter decomposition in the worst and second worst years as a function of moisture content and airflow rate for no heat and SC = 10 (2.2 to 2.5°F). (Oct. 15 start, 2°F total temperature rise from fan.)

Energy and performance comparisons for combination drying for St. Cloud, Des Moines and Indianapolis are shown in Table 4. High-temperature drying starting at 28% moisture content is followed by low-temperature drying starting at 22% moisture content. Airflow rates for the low-temperature component are adjusted to yield 0.5% dry matter decomposition in the second worst year for each location. In the worst year it may be necessary to draw grain from the top of the bin and dry it in the high-temperature dryer to prevent excessive deterioration. Comparisons are shown using both ambient air and solar supplemental heat for the low-temperature component of combination drying. Conventional high-temperature drying results are included in the first column for comparison. The results show that combination drying reduces heat energy requirements for the high-temperature dryer from 23,400 Btu per bushel to 8,200 Btu per bushel at all locations. Electrical energy requirements for the low-temperature fan vary due to the different weather conditions at each location. In all cases energy requirements for the low-temperature phase of combination drying are less for the solar supplemented than for the ambient air drying. However, in most cases these additional energy savings are small compared to the significant savings obtained when low-temperature drying is used in combination with high-temperature drying.

In all cases the minimum airflow rate required to reach the dry matter decomposition criteria is less when solar supplementation is used (Table 4). Minimum airflow rates are greatest for Indianapolis where higher ambient air drying temperatures and humidities occur in the Fall leading to more rapid spoilage. Minimum airflow rates are lowest for St. Cloud because of the lower ambient air temperatures, and therefore, lower spoilage rates during the drying season. Horsepower and grain depths are adjusted to yield the constant $2^{o}F$ temperature rise over the fan as the airflows vary in each situation. For the conditions assumed, a $2^{o}F$ temperature rise from the fan corresponds to a static pressure of 2.35 inches of water through the grain mass.

Conditions when the bin reaches 15 1/2% average moisture content and 18% on the top are also included in Table 4. Hours of fan operation are less for the supplemental solar heat than for the ambient air low-temperature drying. More over-drying is incurred with the combination solar systems than with the combination ambient air systems.

Data for the final stop criteria, when the average moisture content of the grain is less than 14% and the top of the bin is less than 15 1/2%, are also shown (Table 4). In many cases the final stop is not reached until the Spring. Dry matter decompositions at the final stop for the top layer are presented for the average, worst and second worst years. For the worst year the dry matter decomposition is greater than 0.5% and for the average year the dry matter decomposition ranges from 0.35 to 0.4%.

Results are also presented for total low-temperature drying from 28% for St. Cloud in Table 4. The stipulation of $2^{o}F$ total temperature rise from the fan means that the depth of fill is limited in this case to

Table 4. Energy and performance comparisons for combination drying (change to low-temp. at 22% w.b.)[1]

	High-Temp.	St. Cloud Comb. Amb.	St. Cloud Comb. Solar	St. Cloud Low-Temp.	Des Moines Comb. Amb.	Des Moines Comb. Solar	Indianapolis Comb. Amb.	Indianapolis Comb. Solar
Energy input, 1000 Btu/bu								
High-temp. heat	23.4	8.2	8.2	--	8.2	8.2	8.2	8.2
Electric (fans)[2]	0.4	4.1	3.0	6.1	2.6	2.1	3.9	2.5
Operating characteristics								
Initial M.C., % w.b.	28	28	28	28	28	28	28	28
Initial M.C. low-temp, % w.b.	--	22	22	28	22	22	22	22
Airflow rate, cfm/bu	--	1.10	0.98	5.5	1.32	1.17	1.54	1.33
Supplemental heat, °F[3]	--	None	2.3	None	None	2.2	None	2.3
hp per 10,000 bu	--	8.4	7.3	40.7	9.8	8.7	11.4	9.8
Grain depth, ft.	--	15.4	16.0	5.8	14.4	15.1	13.1	14.4
Conditions when bin reaches 15 1/2% ave., 18% top								
Average date: Fall (no. of years)	--	11/29(5)	11/28(8)	10/28(14)	11/14(9)	11/15(10)	11/12(10)	11/12(13)
Average date: Spring (no. of years)	--	4/6(11)	3/21(8)	3/30(2)	3/30(1)	--	4/1(4)	4/1(1)
Ave. year M.C., % w.b.	15.5	15.4	15.2	14.8	14.8	14.1	15.0	14.5
Hrs. of fan operation	--	1613	1307	499	775	861	1117	802
Conditions when bin reaches 14% ave., 15 1/2% top								
Average date: Fall (no. of years)	--	--	--	10/29(7)	11/19(4)	11/21(9)	11/10(4)	11/12(6)
Average date: Spring (no. of years)	--	4/18(16)	4/5(16)	4/8(9)	4/14(6)	3/30(1)	4/13(10)	4/3(8)
Ave. year M.C., % w.b.	--	13.8	13.8	13.7	13.7	13.6	13.6	13.2
Hrs. of fan operation	--	2118	1794	1160	1663	998	1826	1589
Dry mater decomposition top layer, %[4]								
Average year	--	0.35	0.36	0.36	0.37	0.38	0.41	0.40
Worst year	--	0.57	0.59	1.01	0.62	0.62	0.54	0.57
Second worst year	--	0.50	0.50	0.50	0.50	0.50	0.50	0.50

1/ October 15 start, 2°F from the fan. All systems yield same dry matter decomposition in second worst year. There are 16, 10 and 14 years for St. Cloud, Des Moines, and Indianapolis, respectively.

2/ High-temperature fan plus low-temperature fan assuming 85% motor efficiency and fan hours to dry to 15 1/2% average, 18% top.

3/ Supplemental solar heat based on a solar coefficient of 10 as defined by Pierce and Thompson (8).

4/ Dry matter decomposition at final stop (14% ave., 15 1/2 % top).

5.8 feet with a 40-horsepower fan requirement for 10,000 bushels. The The minimum airflow rate required is 5.5 cfm per bushel for ambient air drying. The total energy requirement for this system is quite low, indicating that total low-temperature drying with ambient air can be efficient and can accomplish the desired results if grain depths are restricted. The 5.8 foot depth corresponds to a bin diameter of approximately 53 feet for 10,000 bushels. This along with the high horsepower requirement makes the feasibility of such systems questionable at this time.

Energy and performance comparisons are included in Table 5 for the case where the airflow rate is held constant for the low-temperature drying at 1 cfm per bushel yielding a 16 foot grain depth and 7.3 horsepower per 10,000 bushels. The initial moisture content for low-temperature drying is adjusted to insure that the system reaches 0.5% dry matter decomposition in the top layer in the second worst year. In all cases, the addition of supplemental solar heat provides for a slightly increased moisture content at the changeover from high-temperature to low-temperature drying to yield the same dry matter decomposition. The moisture content at changeover is greatest for the St. Cloud location and lowest for the Indianapolis location.

An economic analysis of the energy savings due to supplemental solar heat low-temperature drying, compared to ambient air low-temperature drying is included in Table 6. Electrical and propane energy savings are included for the conditions shown in Tables 4 and 5. Estimates of collector area required to deliver this heat are used to develop annual cost and first cost comparisons for collectors. In these comparisons the following assumptions are made:

1. No additional energy is required to move air through the collectors.

2. Differences in horsepower requirements and bin depths for the ambient and solar supplemented systems are neglected or assumed not to be significant for the cost comparisons.

3. All comparisons are based on solar energy collected on a horizontal surface with a 40% collection efficiency.

4. Current energy prices as listed in the table are assumed.

5. An annual cost for the collectors of 20% of first cost is used. The capital recovery cost for a collector of 10-year life at 10% interest is 16.3% of the first cost. This leaves 3.7% for annual energy and maintenance costs.

The results indicate that the collector costs that can be justified for supplemental solar energy are small, ranging from 15¢ to 40¢ per square foot of collector. This estimate is based on a horizontal collector

Table 5. Energy and performance comparisons for combination drying (1 cfm/bu low-temp.).[1/]

	High-Temp.	St. Cloud Comb. Amb.	St. Cloud Comb. Solar	Des Moines Comb. Amb.	Des Moines Comb. Solar	Indianapolis Comb. Amb.	Indianapolis Comb. Solar
Energy input, 1000 Btu/bu							
High-temp. heat	23.4	8.6	8.1	9.7	8.6	10.5	9.7
Electric (fans)[2/]	0.4	3.9	3.0	2.4	2.3	3.5	2.6
Operating characteristics							
Initial M.C., % w.b.	28	28	28	28	28	28	28
Initial M.C. low-temp., % w.b.	---	21.7	22.1	21.2	21.7	20.7	21.1
Airflow rate, cfm/bu	---	1	1	1	1	1	1
Supplemental heat, °F[3/]	---	None	2.3	None	2.0	None	2.2
hp per 10,000 bu	---	7.3	7.3	7.3	7.3	7.3	7.3
Grain depth, ft	---	16	16	16	16	16	16
Conditions when bin reaches 15% ave., 18% top							
Average date: Fall (no. of years)	---	11/30(2)	11/28(9)	11/23(9)	11/19(10)	11/20(7)	11/18(12)
Average date: Spring (no. of years)	---	4/5(14)	3/22(7)	3/30(11)	---	4/2(7)	3/31(2)
Ave. year of M.C., % w.b.	15.5	15.4	15.2	14.8	14.2	15.1	14.7
Hrs. of fan operation	---	1725	1289	1039	886	1495	1092
Conditions when bin reaches 14% ave., 15 1/2% top							
Average date: Fall (no. of years)	---	---	---	11/29(4)	11/26(8)	11/20(3)	11/19(5)
Average date: Spring (no. of years)	---	4/5(6)	4/6(2)	4/15(6)	4/6(2)	4/25(11)	4/5(9)
Ave. year of M.C., % w.b.	---	13.8	13.8	13.7	13.5	13.5	13.3
Hrs. of fan operation	---	2207	1779	1793	1265	2277	1786
Dry matter decomposition top layer, %[4/]							
Average year	---	0.35	0.35	0.36	0.38	0.42	0.40
Worst year	---	0.56	0.59	0.56	0.65	0.67	0.53
Second worst year	---	0.50	0.50	0.50	0.50	0.50	0.50

1/ October 15 start, 2°F from the fan. All systems yield same dry matter decomposition in second worst year. There are 16, 10 and 14 years for St. Cloud, Des Moines, Indianapolis, respectively.

2/ High-temperature fan plus low-temperature fan assuming 85% motor efficiency and fan hours to dry to 15 1/2% average, 18% top.

3/ Supplemental solar heat based on a solar coefficient of 10 as defined by Pierce and Thompson (8).

4/ Dry matter decomposition at final stop (14% ave., 15 1/2% top).

Table 6. Economic comparison for combination, low-temperature ambient versus combination, low-temperature solar drying.

Location	Propane Savings[1] 1000 Btu/bu	Propane Savings[1] Gal/bu[2]	Electric Savings[1] 1000 Btu/bu	Electric Savings[1] kWh/bu[3]	Annual Fuel[4] Savings, ¢/bu.	Collector[5] Area, Sq.ft./bu	Annual[6] Cost, $/ft^2	First[7] Cost, $/ft^2
Change to Low-Temperature								
at 22%, adjust airflow								
St. Cloud	---	---	1.1	0.32	1.3	0.18	0.072	0.36
Des Moines	---	---	0.5	0.15	0.6	0.21	0.029	0.15
Indianapolis	---	---	1.5	0.44	1.8	0.23	0.078	0.39
1 cfm/bu, adjust M.C.								
St. Cloud	0.5	0.005	0.9	0.26	1.3	0.18	0.069	0.35
Des Moines	1.1	0.012	0.1	0.03	0.6	0.18	0.033	0.17
Indianapolis	0.8	0.009	0.9	0.26	1.4	0.18	0.078	0.39

1/ Energy savings due to using supplemental solar heat on the low temperature phase versus ambient air.

2/ 91,600 Btu/gal propane.

3/ 3,413 Btu/kWh.

4/ Based on $0.40/gal of propane and $0.04/kWh electric.

5/ Assumes 40% collection efficiency for a horizontal surface.

6/ Annual value of fuel savings per sq. ft. of collector area.

7/ First cost that can be justified for a collector based on the assumption that annual cost savings are 20% of the first cost of the collector.

surface of 40% efficiency. If the collector were oriented at an optimum angle to the sun and the efficiency were increased to the 50% range the same amount of energy could be captured with approximately half of the surface area. This would allow a cost of double that estimated, or 30¢ to 80¢ per square foot. However, orienting the collector at an optimum angle and increasing the efficiency would probably lead to increased collector costs in most cases. Where low cost collectors can be developed, possibly as part of the structure in new buildings, these values may be near the economic break-even point.

This economic analysis has attempted to compare only the primary energy cost effects. As indicated, differences in equipment requirements such as fan horsepower and bin depths are ignored. In many cases these cost differences will be small or nonexistent. Also, some additional energy will be required to move air through the flat plate collectors resulting in additional energy input and energy cost. If collectors are efficiently designed this amount may be minimal. However, indications from recent experimental work indicate that collector energy inputs can be significant (e.g. Morey et al., 5).

SUMMARY AND CONCLUSIONS

Potential energy savings by using combination high-temperature, low-temperature drying have been evaluated. Results have been presented which show the additional energy savings that can be obtained in the low-temperature component by adding supplemental solar heat to low-temperature ambient drying. Based on these results, several general conclusions can be drawn:

1. Combination high-temperature, low-temperature drying significantly reduces propane or natural gas energy requirements for drying corn.

2. Although electrical energy requirements (measured at the point of use) are increased using combination methods, total energy use for drying corn is significantly decreased.

3. Additional energy savings obtained with solar supplementation of ambient air for the low-temperature phase are modest compared to the significant savings which occur when low-temperature drying is used in combination with high-temperature drying.

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MULTIPLE USE SOLAR HEAT

COLLECTION AND STORAGE SYSTEM FOR GRAIN DRYING

Ralph W. Hansen[1] and Charles C. Smith[2]

A disadvantage in utilizing solar equipment for grain drying is the relatively short period of the year during which the equipment is operated. As a result, the cost effectiveness is poor, due to the large portion of the year that the equipment remains idle. To extend the utilization of the solar collection and storage equipment beyond grain drying, a project was established at Colorado State University to investigate the multiple use concept for the solar collection and storage facilities. By utilizing the equipment for different applications, its use can be extended throughout the year. Therefore, the initial investment can be increased to provide more efficient, more durable equipment, utilized for several purposes, and maintain a reasonable cost per heat unit. An ideal situation would be to establish a constant demand to utilize the energy from the collection equipment on a year-round basis.

A farm lends itself well to the multiple use concept. Possible applications include grain drying, forage drying, space heating for homes, farrowing houses, calf and poultry houses, machine shops, water heating for domestic or dairy use and, possibly, space cooling for homes or livestock buildings.

Each application will have variations in its demand for energy. Each alternative must be investigated individually as well as collectively to determine the possibilities for solar application of the multiple use system. Some of the objectives of this project include establishing requirements and relationships between various applications and the solar heat collection and storage facilities. Design criteria can then be developed for agricultural applications based on climatic and economic considerations. Existing references are being utilized to establish space and water heating energy requirements for particular applications (5). As an example, Christianson and Hellickson (2) recently reported on simulation and optimization of energy requirements for livestock housing. They have developed a computer program which takes into account humidity, wind, temperature and insulation requirements or constraints for space heating of agricultural buildings. This program may be utilized in the future to generate design tables for various applications utilizing solar energy as the heat source.

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[1]Associate Professor, Department of Agricultural and Chemical Engineering, Colorado State University, Fort Collins.

[2]Research Associate, Solar Energy Applications Laboratory, Colorado State University, Fort Collins.

The concept of a seasonal application of solar energy resources for a multiple use system is illustrated in Figure 1, showing how various types of agricultural operations might utilize solar heat during different seasons.

CSU SOLAR GRAIN DRYING PROJECT

The solar grain drying facilities at Colorado State University were designed as a demonstration-research scale model of a solar collection, drying and heat storage system for low-temperature grain drying. A low-temperature drying system was selected since it is easily adapted to existing storage facilities and combines more harmoniously with the multiple use aspect. The unit was constructed on a scale to provide actual operational characteristics while keeping costs to reasonable levels.

The system consists of a conventional, commercially available air-type, flat-plate collector with a double glass cover. A centrifugal fan powered by a one-third horsepower motor draws the heated air from the collector. The air control system determines the mode of operation, depending on drying conditions. Assuming heat is being collected, the system is in the collector mode. This is determined by the temperature difference between the collector and ambient sensors, providing for a flow, as illustrated in Figure 2A. Air will flow to the plenum in the lower part of the bin through the perforated floor and up through the grain mass.

The top of the bin is sealed to provide for collecting the air after it passes through the grain and directing it by the air-handler to the rock bed heat storage.

The system will remain in the collector mode until the temperature difference falls below the "collector low" setting. When the collector temperature falls below the low setting, it shuts off the system. Then, if the difference between the storage sensor temperature and the ambient sensor temperature is greater than the setting for the storage high, the mode will be shifted to storage, as illustrated in Figure 2C. It will remain in this mode until the temperature difference falls below the storage low setting or until a temperature difference between the collector sensor and the ambient sensor is greater than the collector high setting. This shows that the system is biased towards the collector, meaning the collector mode will take precedence whenever the difference between the collector and ambient sensors is greater than the collector high setting.

The rock bed storage, during reverse flow, was used to provide an extension of the drying operation. This was accomplished by utilizing the surplus heat from the dryer unit during daytime operation. When weather and grain conditions are suitable, some surplus heat can be collected and utilized during nighttime operation. In addition, it was expected that the reverse flow would provide more uniform drying through

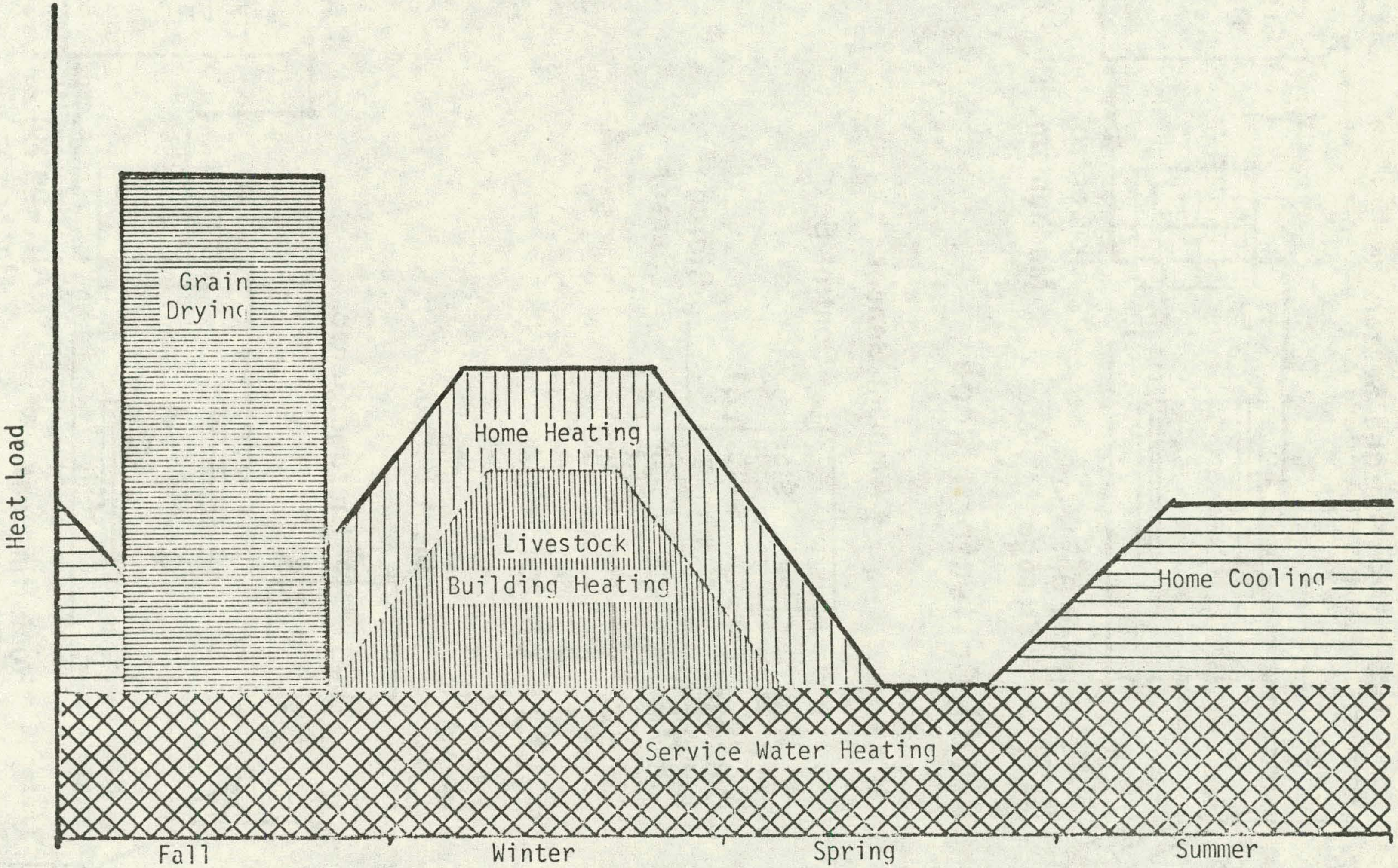
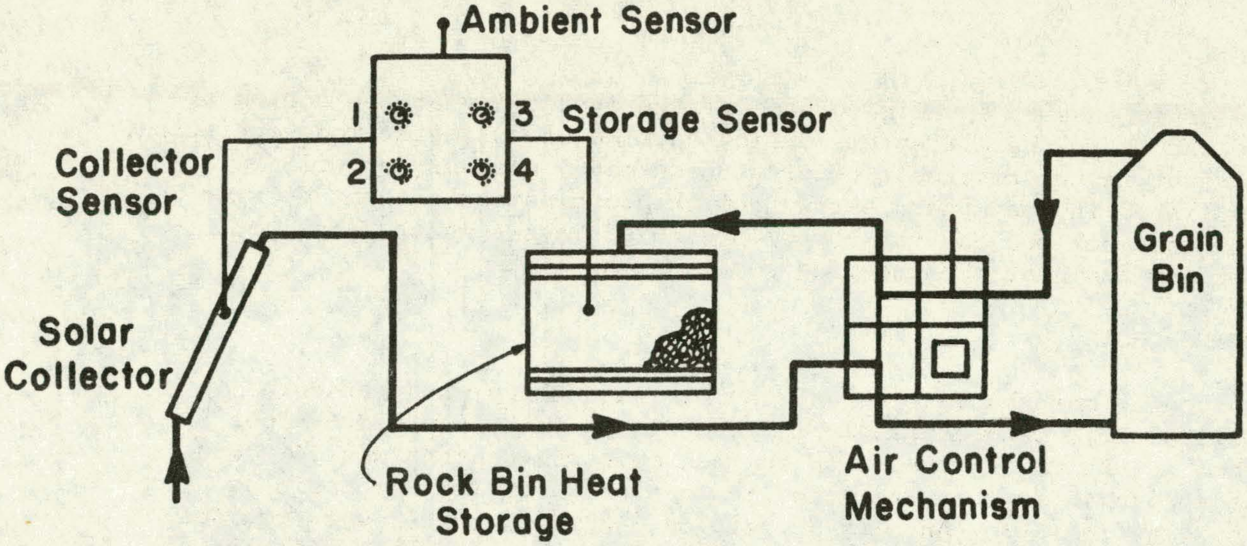
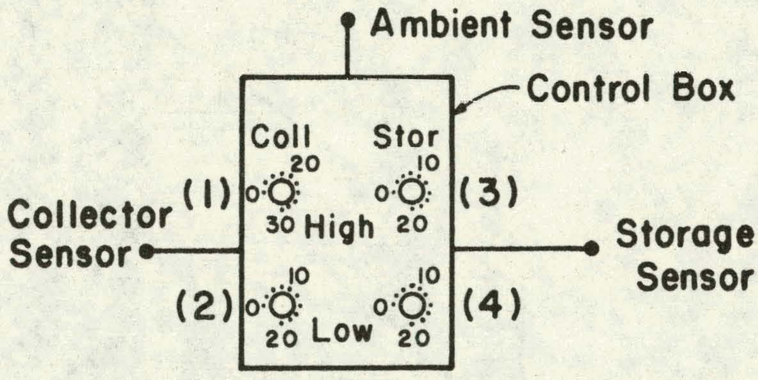


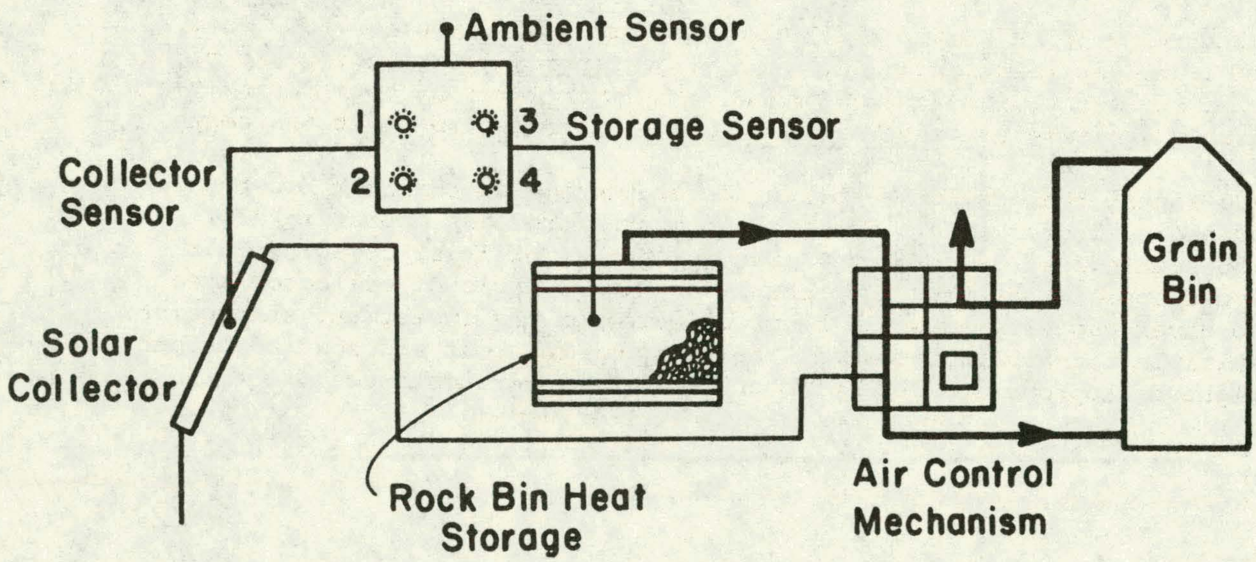
Figure 1. Representation of Farmstead Seasonal Demands for Heat Energy



(a) Collector Mode



(b) Control Box



(c) Storage Mode

Figure 2. Grain Dryer Flow and Control Diagram

the grain mass by equalizing some of the overdrying at the bottom of the bin where the air enters during daytime or collector mode operation. At night in the reverse flow or storage mode, some drying will be accomplished in the upper layers from the combination of heat storage from the rock bed and the bottom overdried layers which serve to further dry and heat the incoming cooler night air.

DRYING TESTS

As soon as corn harvest began, the bin was filled with wet corn (October 26). Approximately 125 bushels of corn provided 6½-foot depth in the drying bin. The initial moisture content was 24½% wet basis. In 16 days it was dried to an average of 15% wet basis as shown in Figure 3. An airflow rate of 3 cfm per bushel was provided. This resulted in an average air temperature rise from the collectors of 15°F above ambient. Typical temperatures for a 24-hour period are illustrated in Figure 4. After the air passed through the grain, the temperature of the drying air was reduced to approximately ambient temperature, therefore, providing limited heat for storage in the rock bin. Daytime temperatures were still fairly warm so even daytime ambient temperatures in the rock bed did provide some heat storage to provide better nighttime drying temperatures than could be obtained from direct use of ambient air.

The second filling of corn was begun on November 15. An airflow rate of 2 cfm per bushel was used for this drying run. An average temperature increase of approximately 15°F was obtained from the collectors with this airflow rate as shown by Figure 5.

This batch of corn was put in the dryer at 26% wet basis and dried to 15% wet basis in 21 days. Again, the heat storage facility did not realize any significant temperature gain above ambient during the day but was still of some benefit during the colder, nighttime temperatures, as illustrated by the temperature curves on Figure 5.

Overdrying of the lower layers of corn was again experienced. Some moisture was transferred back to the overdried layers during the nighttime operation with some drying of the upper layer of corn during the night, but moisture conditions were not uniform throughout the depth.

Additional heat could be collected for storage in the rock bin by adding collector area. The present system provides approximately .56 square feet of collector area per bushel of dryer capacity. It would appear that this is probably as high a ratio of collector area to dryer capacity as would be practical from the investment standpoint. Multiple use applications will help spread the cost and some adjustment might be appropriate depending on individual circumstances.

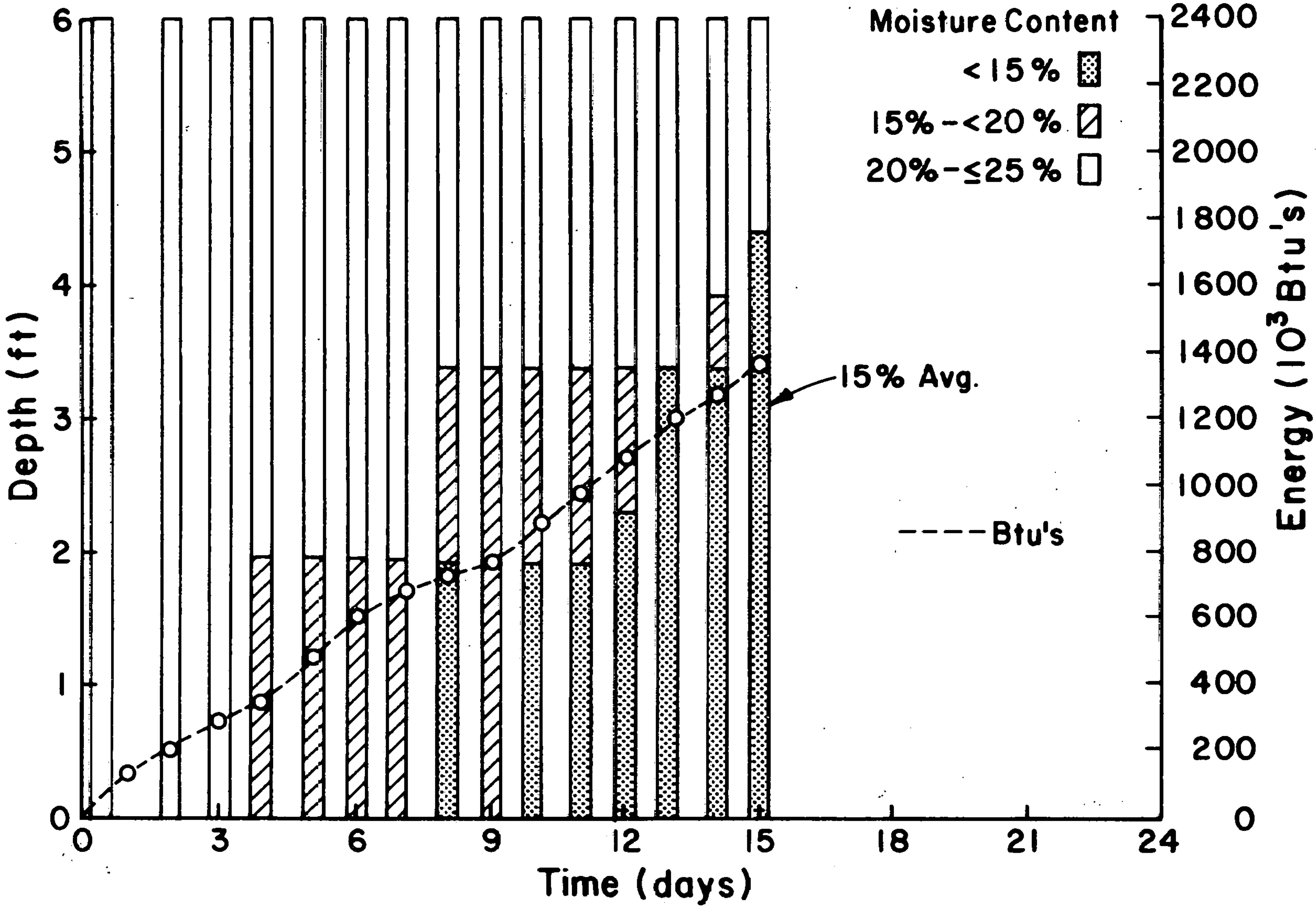


Figure 3. Grain Moisture Content vs. Time

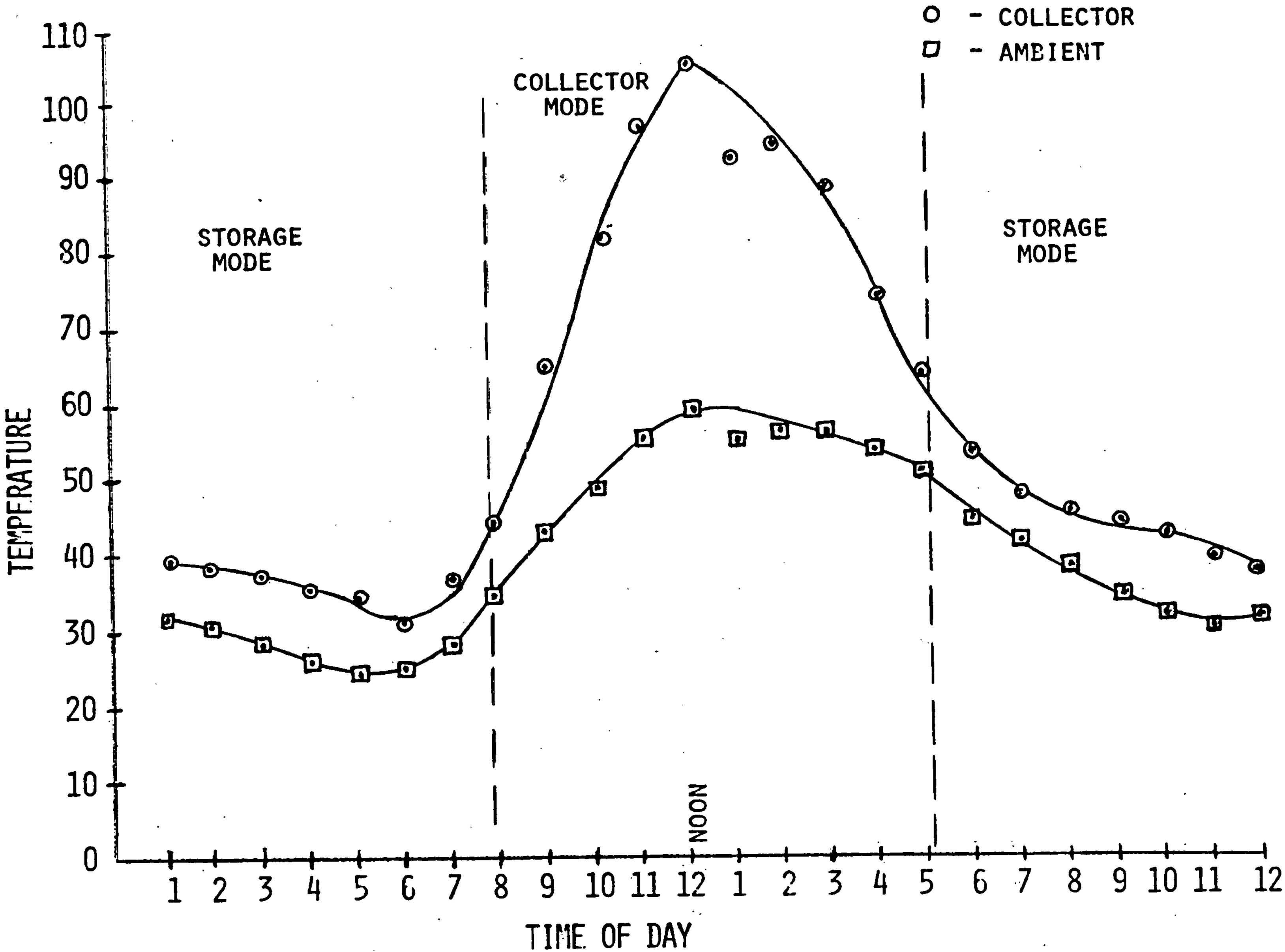


Figure 4. AVERAGE COLLECTOR AND AMBIENT TEMPERATURES (26 OCT. - 3 NOV.)

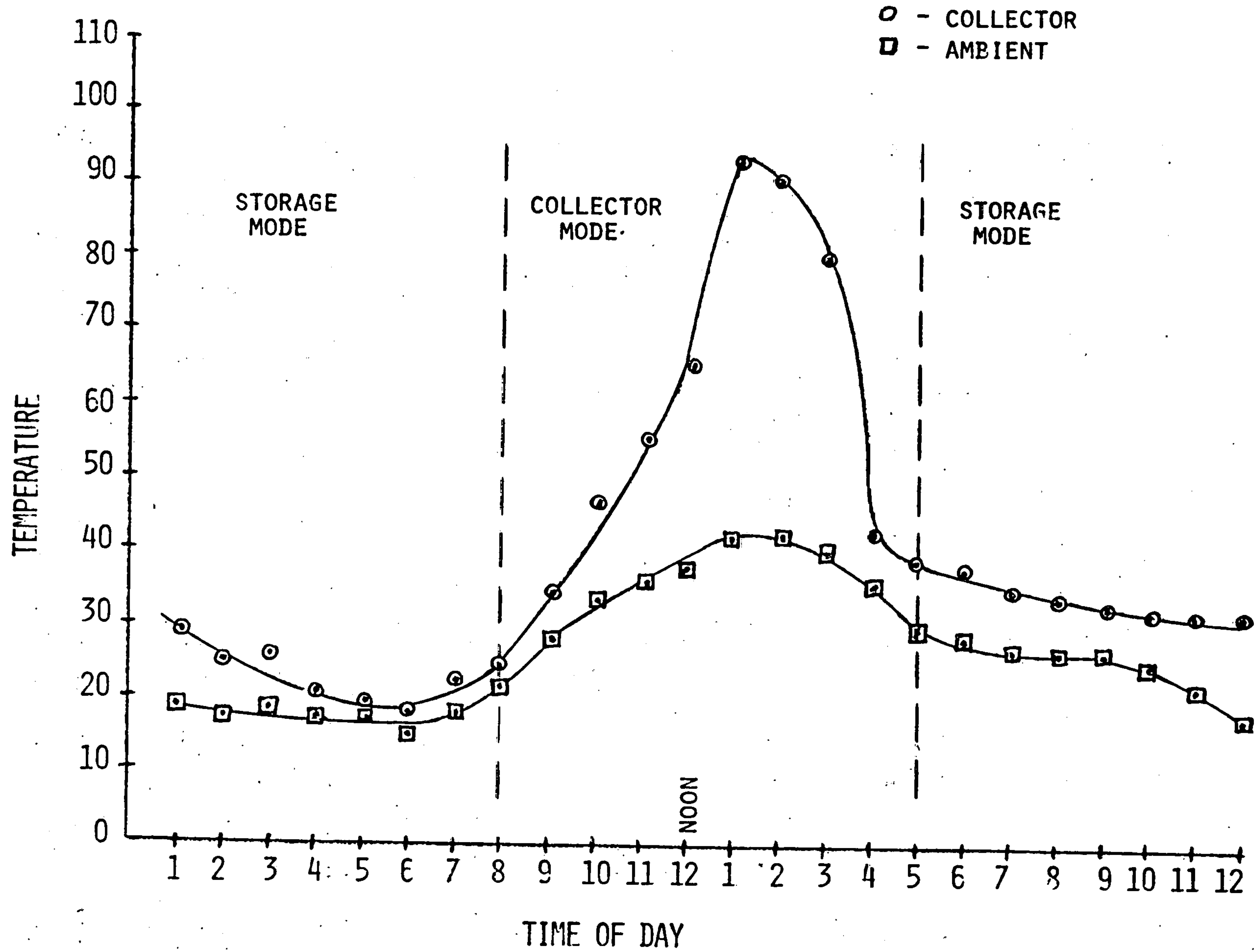


Figure 5. AVERAGE COLLECTOR AND AMBIENT TEMPERATURES (NOV. 15 - DEC. 4)

WATER HEATING EXPERIMENTS

An alternate use suggested for the solar collectors was heating of dairy wash water. Water heating tests were made using an air-to-water heat exchanger (Figure 6).

The counterflow heat exchanger was designed for the 70 square foot collector area and used an insulated 30-gallon storage tank. An airflow rate of 140 cfm (2 cfm/ft^2 of collector) was used for the initial tests. Water flow could be varied depending on the temperature gain desired.

For test purposes, the operation of the water heating system was manual with the exception of an electronic flow valve that stopped air and water flow when the storage tank was filled with hot water. A low-temperature, shut-off thermostat could be coupled with the system to prevent operation when the collector air temperature is lower than the stored water temperature.

Figure 7 illustrates the temperature increases at various flow rates for a typical day's operation. These tests were made with the air from the heat exchanger exhausted to the atmosphere. The efficiency of the system could be improved if the air from the heat exchanger could be recirculated to the collectors.

The system operates most efficiently with a temperature gain of approximately 30°. Adequate heating could be provided for applications such as wash water for prep stalls and, in other cases, serve as a preheater for a conventional water heating system. Higher temperature increases could be obtained with some sacrifice in efficiency and with additional solar collection area.

Water heating for dairy use represents an ideal application for solar energy since the demand is nearly constant the year-round.

OTHER APPLICATIONS

Solar energy can be utilized for a number of space heating types of applications common to farm operations. These include, for example, heating farrowing houses, calf barns, brooder houses, home heating, farm shops and similar applications.

Space cooling, although not used extensively on the farm, would provide an application for summertime utilization of the solar equipment. In addition to home cooling, it might be utilized for some livestock buildings in some areas.

Solar heat can provide the energy for an absorption cooling system. However, the system requires relatively high temperatures and involves a rather sophisticated design. The solar operated absorption cooling system is best adapted to a liquid solar heat collection and storage system.

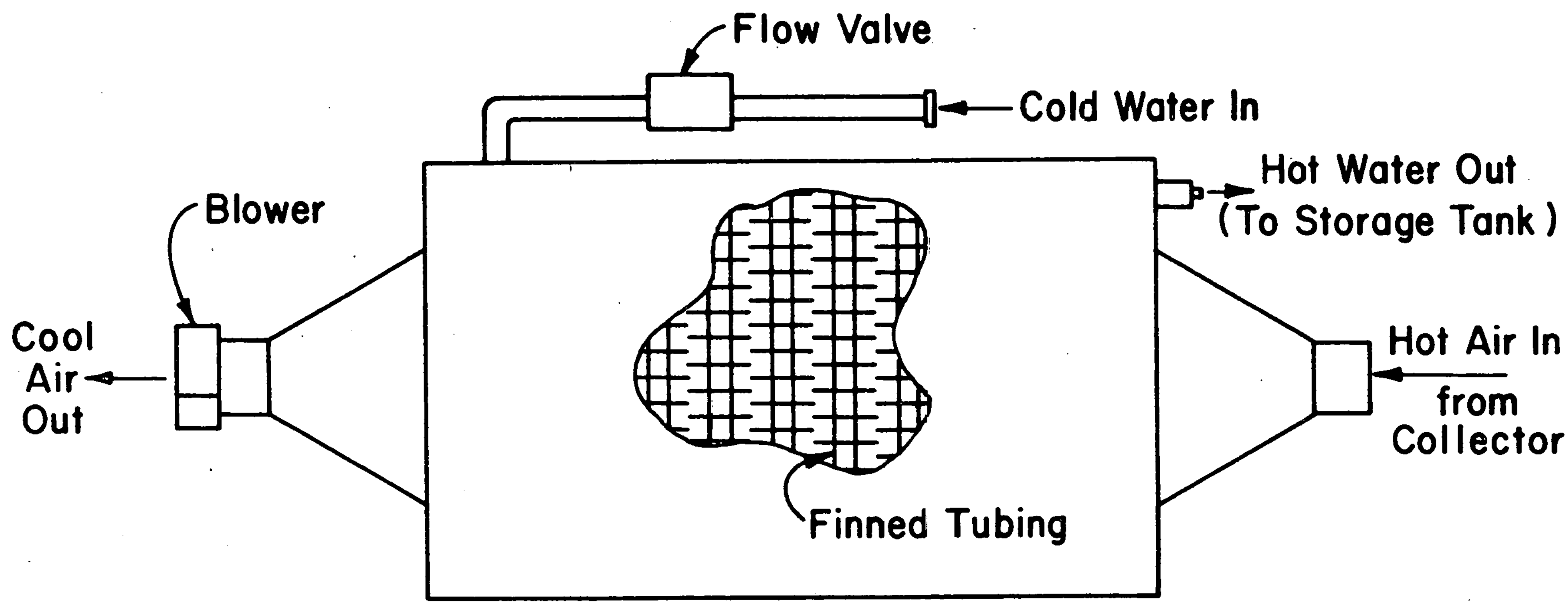


Figure 6. Air-to-Water Counterflow Heat Exchanger

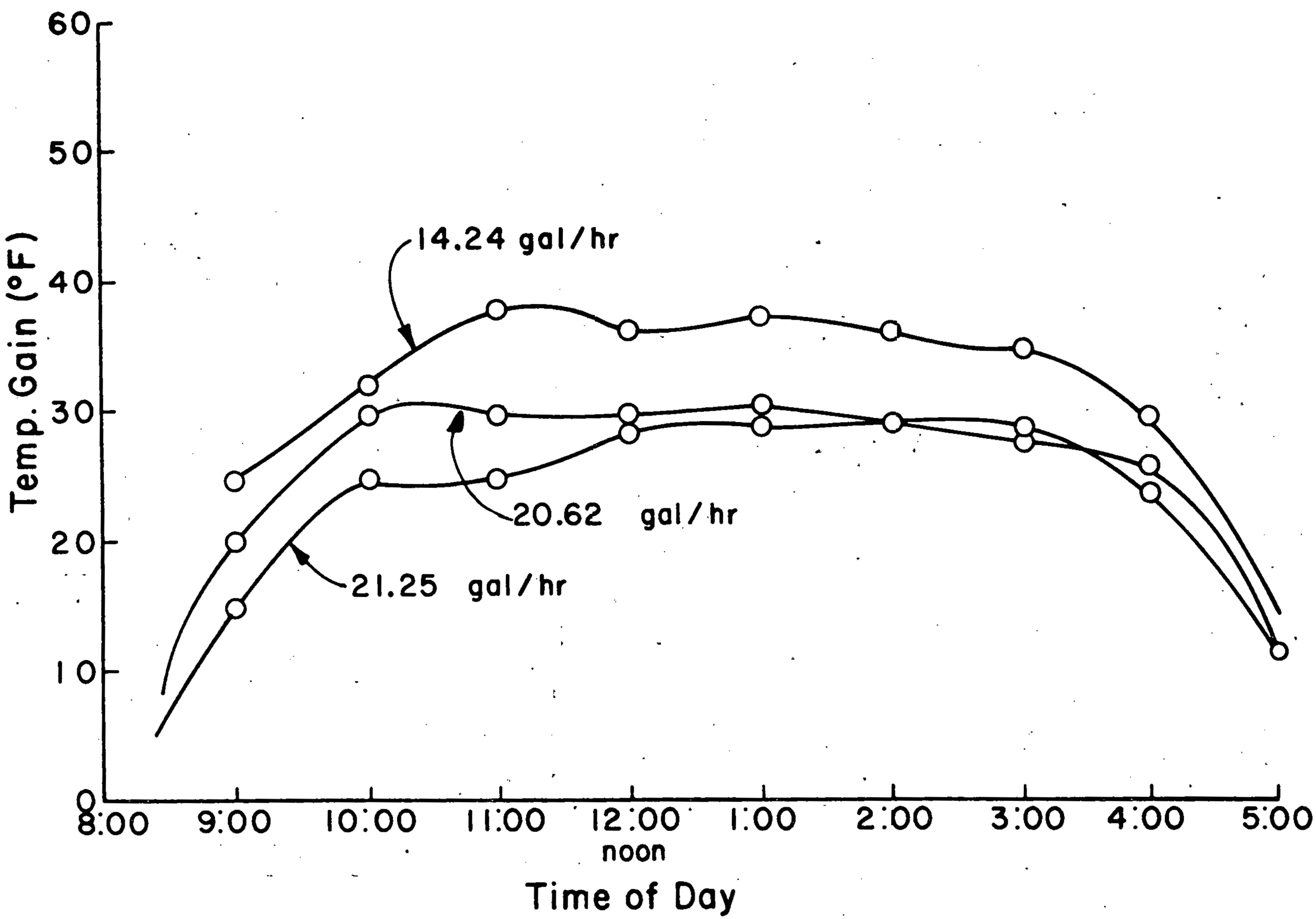


Figure 7. Water Heating Temperature Gain Curves for Water Heating at Various Flow Rates

An alternative better adapted to the air collection and rock storage system could utilize nocturnal cooling. This is restricted to locations where cool, nighttime temperatures are available for cooling the storage bin at night and then utilizing the cooling capacity of the storage during the daytime.

SOLAR ENERGY COLLECTION AND DISTRIBUTION

Multiple use of solar collection and storage facilities would present problems in distribution of the heat to points of application. Two basic approaches could be utilized. They are:

1. A central collection and storage facility with distribution ducts to points of use.
2. Portable collectors moved to point of use.

The most efficient system would probably be provided by a central solar facility serving as the hub of a farmstead operation with applications located in close proximity. An installation of this type would be limited to planning new facilities and not readily adaptable to existing buildings.

To accommodate use at existing buildings, portable collection equipment would be more practical. It would, however, limit the multiple use of the heat storage facilities and require that this part of the system be provided at each location.

The technology and hardware are available to provide the components of the distribution system including the ducts, insulation, blowers, thermostatic controls, air direction dampers and similar equipment needed. Economic considerations are the limiting factors.

SUMMARY

This study on the utilization of solar energy has been based on spreading the investment for equipment over several applications since it is common to each use. If the same equipment can be used for applications occurring during different times of the year, the cost effectiveness is improved. By determining the requirements of various applications, a multiple use system can be designed based on a reasonably well balanced load the year-round.

Conditions will vary locally, necessitating an evaluation of data on climatic conditions, building requirements, solar heat collection potentials and other factors very similar to other design requirements for any building.

Figure 8 illustrates schematically the layout of an agricultural production system that might be developed around a central solar heat collection facility. Our objective will be to provide the design criteria to provide compatible components for the system.

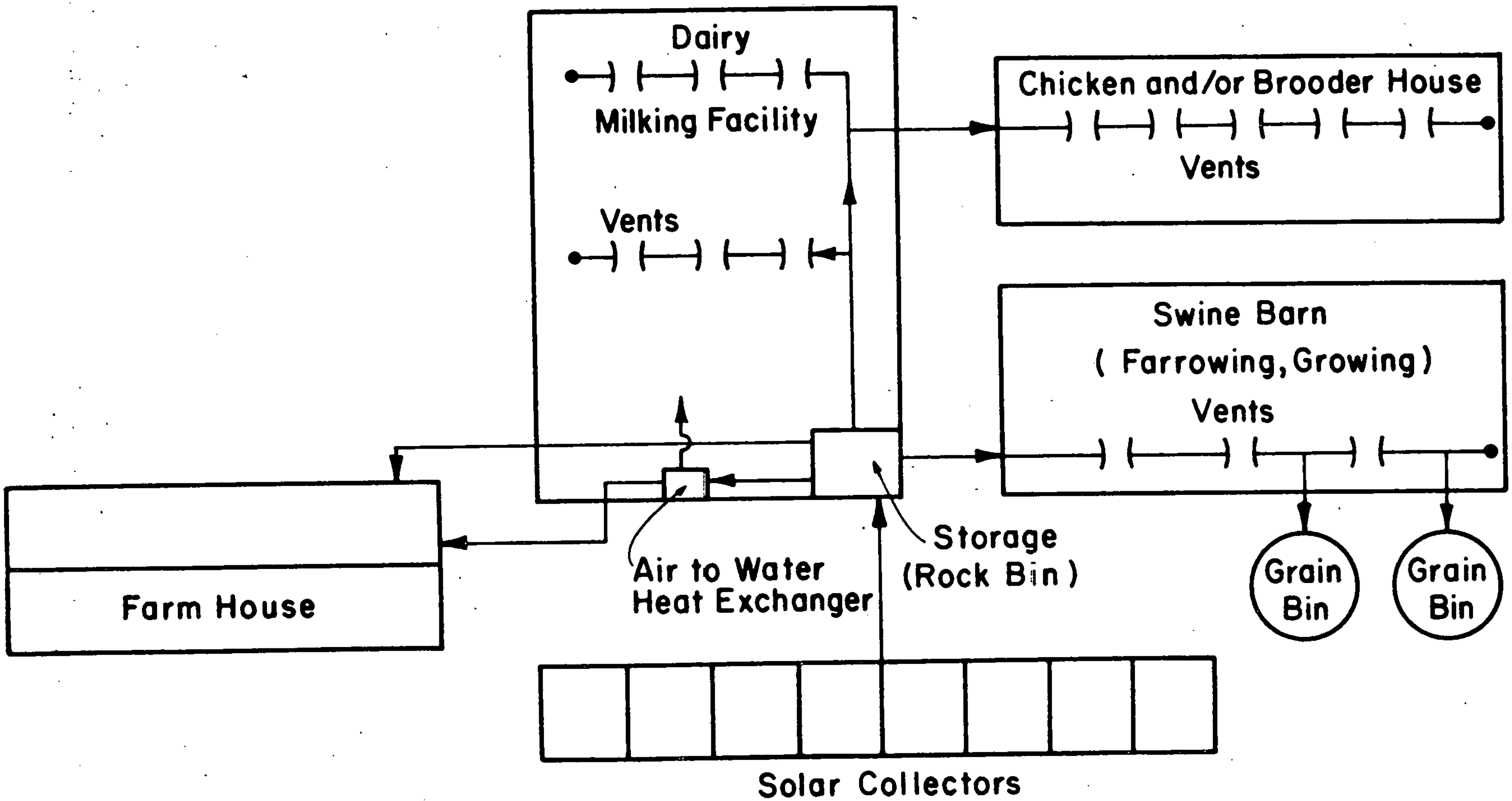


Figure 8. Multiple Use Farm Solar Heat System

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BIN-DRYING WITH STIRRING: RICE

D. L. Calderwood[1]

ABSTRACT

Solar heat aided deep-bed rice drying by reducing drying time and electrical energy consumption for fan operation compared with unheated air-drying. A small reduction in milling yield was noted in rice samples from dryers using solar heated air compared with unheated air-dried samples. The use of a stirring auger did not change the amount of milling yield reduction. The range of moisture contents of rice samples taken as a dryer was unloaded was about the same for samples from a dryer equipped with a stirring auger and solar collector as for samples from a dryer with a solar collector, but without a stirring auger. Stirring augers provided uniform moisture contents of rice at different locations in dryers and eliminated well defined drying zones.

INTRODUCTION

Solar heat is most readily available at the time of day when supplemental heat for in-bin rice drying is neither needed nor desirable, based on recommendations for using supplemental heat by Sorenson and Crane (2). They recommended that supplemental heat (the amount of heat required to increase ambient air temperature by 10° to 12° F) be used only during prolonged periods of high (above 75%) relative humidity. At times when solar heat can be collected, the relative humidity of ambient air generally is at 65% or lower and in a suitable condition for drying rice to a marketable level of 12.5% moisture content. Additional heat, whether from a gas burner, electric element, or solar collector, will increase the difference in moisture content between rice near the air inlet (usually a perforated metal floor) and rice near the air outlet by the time rice in the latter location is dried to 12.5% moisture content. Additional heat also may create stress cracks or "checking" within rice kernels that dry too rapidly. Checked kernels are apt to break when they are milled. A method of protecting rice from long exposure to solar heated air is to move the rice at frequent intervals from one location to another within a bin. This can be accomplished with a vertical stirring auger which picks up material from near the floor and deposits it on the upper surface.

Bin dryers, both with and without stirring augers, were used in tests to determine the effects of solar-heated air on drying rate, milling quality and electrical energy requirements. A dryer equipped with both a solar collector and a stirring auger and another dryer using unheated air without a stirring auger were operated in 1975. These two dryers

[1]Agricultural Engineer, Agricultural Research Service, U. S. Department of Agriculture, Southern Region, Beaumont, Texas.

and two others were tested in 1976. One of the additional dryers had a solar collector, but no stirring auger; the other had a stirring auger, but no solar collector. The solar rice drying test facility is shown in Figure 1.

MATERIALS AND METHODS

The dryers were 9-ft diameter, corrugated steel tanks having a wall height of approximately 11 ft. A perforated steel floor was installed at a level of 1.5 ft above the base. The nominal capacity for drying at an 8 ft depth was 195 cwt of rice. Centrifugal fans with backward curved, 15-in. diameter wheels provided air delivery rate of 1080 cfm against 2.5 in. of static pressure (5.5 cfm/cwt in an 8 ft depth of rice). A 1½ hp electric motor powered each fan.

The vertical stirring augers were especially built for 9-ft diameter drying bins because production models are built only for larger bins. Rotation of the 2-in. diameter vertical auger, powered by a 1½ hp motor, caused rice near the floor to be elevated, then deposited near the surface. Each auger was supported on a carriage which moved back and forth along a horizontal tube having spiral flighting. The horizontal tube was coupled to a 1 rpm, reversible gear motor. Counterclockwise rotation of the gear motor and tube (as viewed from above) moved the carriage toward the bin wall and caused counterclockwise displacement of the tube in relation to a track around the bin wall. When the carriage reached a point about 6 inches from the wall, a reversing switch changed the direction of rotation of the gear motor moving the carriage towards the center of the bin. While the carriage moved in this direction, the horizontal tube remained stationary in relation to the bin wall. Another reversing switch was operated when the carriage arrived at the center of the dryer. The time for a complete counterclockwise movement of the horizontal tube around a 9-ft diameter dryer was approximately 2 hours. Since the horizontal tube started from a different point on the track following each complete revolution around the dryer, the vertical auger came into contact with nearly all rice in the dryer during an operating period of several hours.

The absorbers of solar collectors were sheets of corrugated steel roofing painted flat black. These sheets formed the surface of a tunnel 4 ft wide, 48 ft long and 6 in. deep. A 3-in. thickness of glass wool insulation covered the plywood floor. In 1975, the absorber was covered with 6 mil, clear polyethylene sheet. A small fan inflated the polyethylene sheet and created a movement of heated air towards the intake of the dryer fan. Clear, corrugated, fiberglass sheets were used as covers for absorbers in 1975. Since this material was fairly rigid, a solar collector could be connected to the suction side of the dryer fan in order to eliminate the small fan previously used for inflating a polyethylene cover and for moving air through a solar collector. In 1976, tests were run both with and without the small fan. The solar collectors were oriented in a north-south direction with a slight inclination towards the south.

Time switches, thermostats and humidistats were used in various combinations to control the operation of fan and stirring auger motors. In the 1975 test, the stirring auger ran continuously, but in 1976, the stirring augers were operated by a time switch from 0800 to 1700 CST daily. Solar collector fans were operated between sunrise and sunset by means of another time switch. The fans attached to each dryer were operated continuously until rice near the top surface was dried to below 16% moisture content. After this time, each of these fans was controlled by a humidistat for operation whenever ambient air relative humidity was 65% or lower. In addition, the fans moving solar-heated air were actuated by a thermostat so that operation occurred whenever solar-heated air was at a temperature of 95° F or higher.

Energy requirements were estimated in 1975 based on the total time of operation of each electric motor and a short-term hookup of a watt-hour meter to each motor. In 1976, a kilowatt-hour meter was installed on each dryer and the total electric consumption of all motors used at a particular dryer was recorded.

Rice samples were taken at regular intervals as each dryer was loaded and again as a dryer was unloaded. Individual samples were tested for moisture content, then all samples from a particular operation were blended to make up a composite sample for a milling yield test. Composite samples taken as a dryer was loaded were dried to 12% moisture content using unheated air in a conditioning room. These samples are identified as "control" samples in milling yield data. Samples for moisture tests were taken at daily intervals from the top, center and bottom of dryers.

Temperature observations were made at irregular intervals in 1975, but temperatures were recorded at hourly intervals in 1976 by thermocouple junctions placed at various locations and connected to a recording potentiometer. These locations included the plenum chamber of each dryer and the intake and exhaust air stream of solar collectors. The maximum temperature rise noted in a plenum chamber due to heat from a solar collector was 18° F. The average plenum chamber temperature rise during 10-hr daily collecting periods throughout several days of a drying operation was approximately 10° F.

Air flow rates were computed from air velocity measurements as the exhaust air passed through the top openings of dryers. The top openings were measured to determine their cross-sectional area. Static pressures in plenum chambers and depth of fill of dryers were noted in order to provide another estimate of air flow rates by use of a graph published by Shedd (1). Using either method of computing air flow rates, the air flow rate was somewhat higher than 1080 cfm in Dryers 3 and 4 with stirring augers and less than this amount in Dryers 1 and 2 without stirring augers. The higher rates of air flow in Dryers 3 and 4 may have been due in part to a reduction in resistance of rice to air flow because of stirring action but having a depth of fill less than 8 ft might account for the higher air flow rates.

RESULTS AND DISCUSSION

Effects of solar heat: Table 1 shows that drying time was shorter for each bin of rice having a solar heat drying treatment, compared with rice of the same variety and initial moisture content, loaded into a dryer at the same time, but dried with unheated air. The shorter drying times reduced electrical energy consumption in 1976 tests. Continuous operation of the stirring auger in the 1975 test caused greater electrical energy consumption for rice dried with solar heat compared with unheated air-dried rice.

Milling yield data in Table I indicates that using heat from solar collectors for faster drying generally resulted in reduced milling yields when dryer-dried samples are compared with control samples or with unheated air-dried samples from another dryer. However, the maximum tabulated difference is only 1.6% whole kernels of milled rice and the average difference is less. The advantages gained from faster drying include marketing a batch of rice sooner and drying other batches in the same dryer. These advantages can more than offset the loss from a small drop in milling yield.

Effects of stirring augers: Rice samples from the top, center and bottom of dryers with stirring augers seldom were more than 1 percentage point different in moisture content. A difference of 6 percentage points, and more, commonly was noted between the top and bottom samples from a dryer without a stirring auger. Uniform moisture content distribution reduces the hazard of quality loss due to spoiling that may result when rice at the top of the dryer remains at an excessively high moisture content too long.

Moisture tests of samples taken at regular intervals as the dryers were unloaded indicated about the same range of values regardless of whether rice had been stirred or remained stationary. Moistures ranging from 11.7 to 10.8% were noted in rice samples from Dryer 3, using both solar heat and a stirring auger; moistures ranging from 12.0 to 11.2% were noted in samples from Dryer 1 using solar heat but no stirring auger.

It is not clear from data listed in Table 1 whether or not the use of stirring augers either aided faster drying or reduced damage to milling yield; however, data for Dryer 1 indicates that solar rice drying can be carried out successfully without stirring augers if an air flow rate of 5.6 cfm/cwt is provided, initial moisture content of rice is less than 20%, the depth of fill is limited to 8 ft and daily average temperature rise is no more than 10° F.

CONCLUSIONS:

1. Use of solar heat reduced the elapsed time for drying compared with unheated-air drying.

2. Use of solar heat reduced the electrical energy requirement for fan operation compared with unheated-air drying.

3. Use of stirring augers provided uniform moisture content distribution throughout drying bins and eliminated well defined drying zones.

4. Solar rice drying can be carried out successfully without a stirring auger if the depth of fill is limited to 8 ft; moisture content is limited to 20%; air temperature rise is limited to 10° F and an airflow rate of 5.5 cfm/cwt is provided.

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Figure 1. Solar rice drying test installation in 1975. Shown from left to right: Bin 1, with a solar collector and no stirring auger; Bin 2, without a solar collector or stirring auger; Bin 3, with both a solar collector and a stirring auger; Bin 4, with a stirring auger but no solar collector.

TABLE 1 Effect of solar heat and stirring of rice in bin dryers on drying time, electrical energy used and milling yield

Variety	Dryer No.	Treatment: Solar heat	Treatment: Stirring	Starting date	Moisture Content: Initial %	Moisture Content: Final %	Fill depth ft	Elapsed drying time days	Fan operation time hrs	Electrical energy used kWh	Milling Yield[1/]: Control %	Milling Yield[1/]: Dryer-dried %
Bluebelle	3	Yes	Yes	08/23/75	16.6	11.4	7.5	16	117	326	60.1	59.3
Bluebelle	2	No	No	08/22/75	15.2	11.8	7.0	31	213	275	60.0	59.6
Labelle	1	Yes	No	08/19/76	19.6	12.0	7.8	15	206	221	61.5	61.5
Labelle	2	No	No	08/19/76	19.6	12.0	8.3	20	259	326	61.5	63.0
Labelle	3	Yes	Yes	08/18/76	16.0	12.0	7.2	10	139	231	60.2	60.3
Labelle	4	No	Yes[2/]	08/17/76	16.0	12.0	7.1	19	246	321	60.2	60.3
Lebonnet	3	Yes	Yes	09/09/76	17.8	11.5	7.1	16	218	292	57.0	55.7
Brazos	3	Yes	Yes	09/29/76	17.5	12.2	7.0	13	217	281	62.7	61.1
Brazos	4	No	Yes	09/29/76	17.5	12.2	6.7	20	278	377	62.7	61.7

[1/] Whole kernels of milled rice

[2/] Because of breakdowns, stirring auger operated only 7 days.

STIRRING OF CORN FOR SOLAR HEATED IN-BIN DRYING

Robert M. Peart[1]

A vertical stirring auger was used in 1975 and 1976 in solar drying tests with corn in an 18-foot diameter bin with grain depths of about 10 feet. The unit was manufactured by Sukup Manufacturing and had a single vertical auger with a 1.5 HP motor on a vertical auger and a .25 HP motor on the horizontal shaft which caused rotation around the bin as well as a back and forth motion along the radius.

EFFECT ON MOISTURE DISTRIBUTION

In the 1976 drying test, moisture contents were taken periodically in the stirred and the unstirred bins, and they are shown in Figures 1 and 2. Notice that the stirred bin exhibited very uniform moisture contents except in the bottom one foot layer which was not affected much by the stirring auger. In the unstirred bin, the typical drying front and drying zone are shown.

EFFECT ON AIR FLOW

Air flow measurements were made across the top surface of the bin and in the air duct, and these were compared with air flow through the duct in a similar bin that was unstirred. Both bins used a 5 HP centrifugal fan. Because of greater suction pressure due to a horizontal duct added to the intake of the solar heated air fan, the total pressure drop across the 5 HP centrifugal fan was equal in both bins. However, the air flow was also equal through both bins of corn even though the pressure drop across the 10-foot depth of stirred corn was about 73% (2.2 inches of water vs. 3.0) of the pressure drop across the unstirred depth. Air flow measurements at the top surface of the corn showed irregular variations probably due to the distribution of fines and variability of bulk density due to the stirring pattern.

We generally concluded that the stirring auger increases air flow in about the same proportion as would the additional horsepower required by the stirring auger if applied to the fan in an unstirred bin.

EFFECT ON ALLOWABLE DRYING TIME

Our experience indicated that the stirring auger increases the time allowable to complete the drying process in a deep bin. A hypothetical example will show how this is possible. For easy calculations, we will assume constant 60°F (15.6 C) air passing through the top layer in the bin. We will assume that drying proceeds from a beginning moisture content of 26% down to an average of 18% at the rate of 1 percentage point

[1]Professor of Agricultural Engineering Department, Purdue University

per day. In the stirred bin we will assume that the entire bin has a uniform moisture content, while in the unstirred bin we will assume that the top layer stays at 26% moisture until the final day of drying.

A check of the data of Saul and Steele as published by Shove shows that the 26% corn at 60°F has a storage life of 7 days. Our assumption of eight days for drying would put the unstirred bin at the limit of time for 1/2% dry matter loss.

Now let us calculate the storage life used in the stirred situation. We will do this be making calculations every two days, assuming that the entire bin stays at 26% for the first two days, 24% for the next two days, etc. After two days at 26%, 2/7 or 28.6% of the allowable storage life (2 1/2% dry matter loss) is used. At 24% and 60°, the total allowable storage life is 10 days, so the next two days uses up 2/10 or 20% of the allowable storage life, a total of 48.6% after 4 days. At 22%, the allowable storage life is 15 days, and 2 days at 22% equals 13.3% of the storage life. Likewise, 2 days at 20% uses 2/25 or 8% of the storage life. A total of 70% of the allowable storage life is used with the stirring procedure, assuming the same overall drying rate. Thus, the unstirred situation utilizes 100% of the allowable storage life, while the stirring would use only 70% of the allowable storage life.

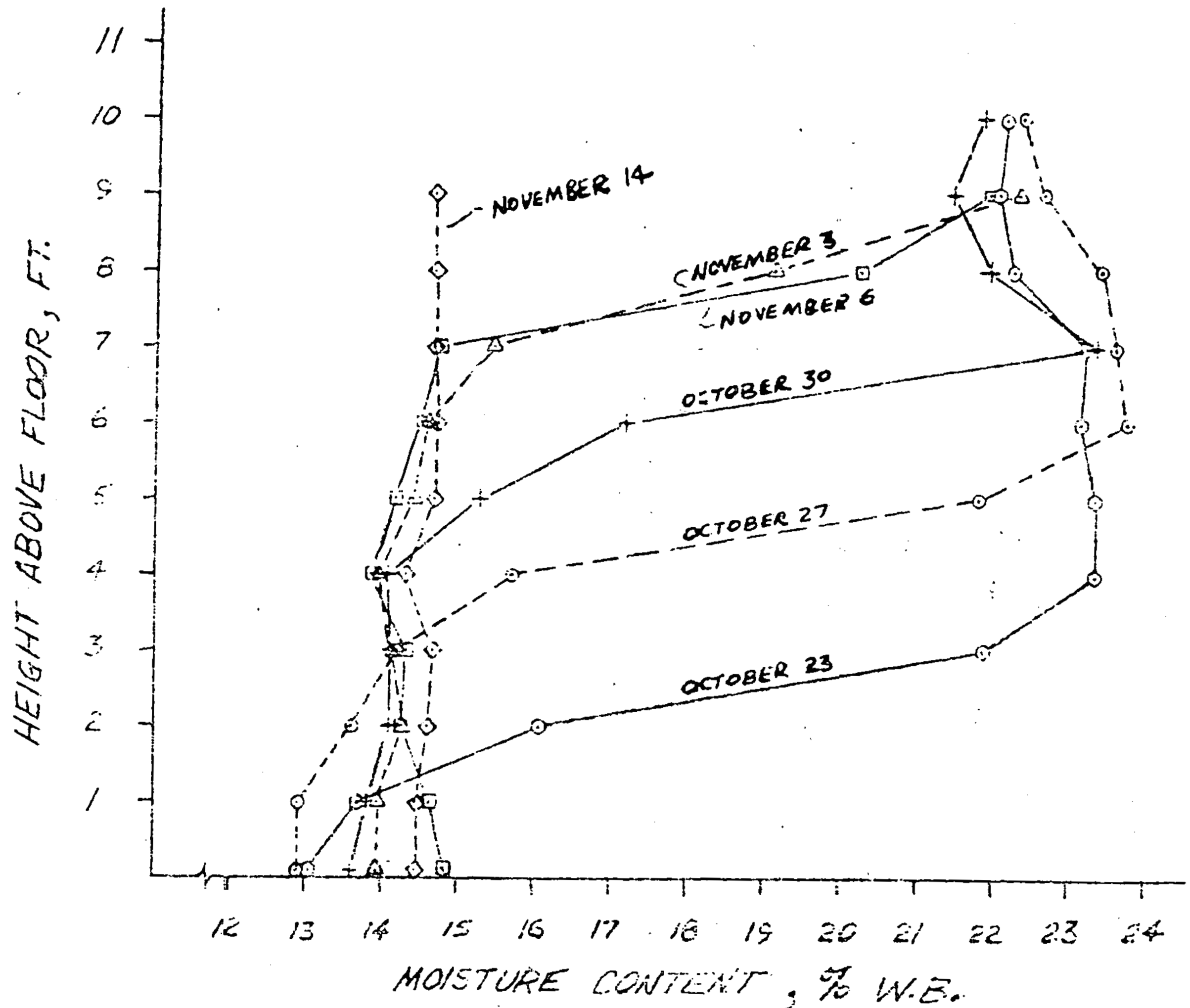

Figure 1. Unstirred bin moisture profiles.

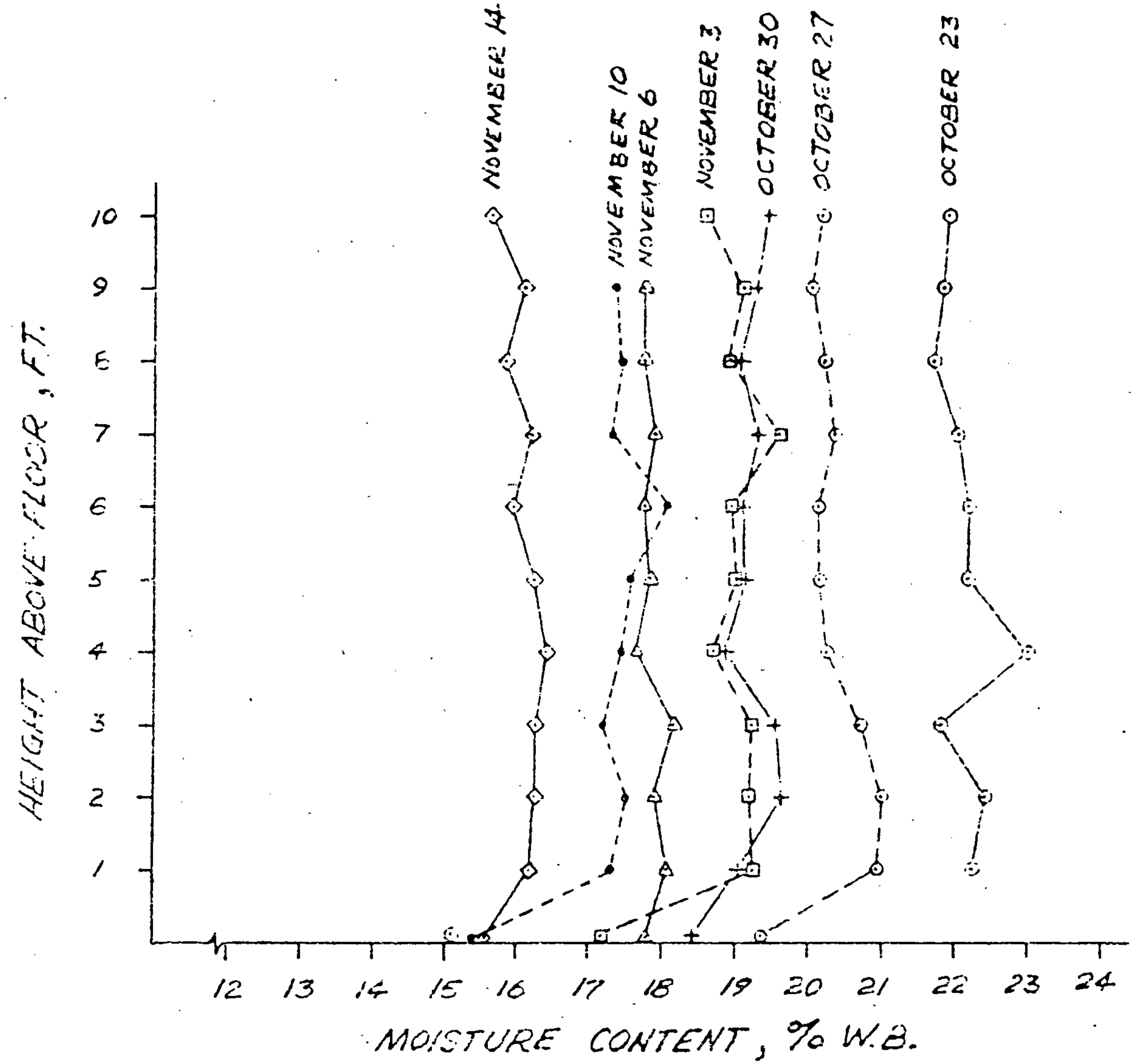

Figure 2. Stirred bin moisture profiles.

SOLAR ENERGY - HEAT PUMP LOW TEMPERATURE GRAIN DRYING

David W. Morrison[1] and Gene C. Shove[2]

INTRODUCTION

Since agricultural production consumes large quantities of petroleum based fuels and products, energy conservation becomes increasingly more important as petroleum supplies diminish and become more costly. Agricultural crop drying, particularly the drying of corn, is a process potentially well suited to the employment of energy conservation practices. Wilson (1976) estimates that an equivalent of 629 million gallons of LP gas are used annually in the United States to dry shelled corn; thus there is the potential for saving a large amount or petroleum based fuels if other energy sources can be effectively used to dry corn.

An energy efficient drying method developed in recent years is the low temperature system. Low temperature drying utilizes air temperatures only slightly above ambient with sufficient airflow to dry grain before any deterioration takes place. Supplemental heat must ordinarily be added to the ambient air to raise the air temperature a few degrees to allow corn to be dried to a safe moisture content. The supplemental heat is usually supplied by electric resistance heating, thus use of petroleum based fuels for heating is eliminated. If alternative heat sources could be utilized, a significant savings in electrical energy could also be realized.

Recently a considerable amount of research has been performed on the applicability of solar energy as a heat source for low temperature drying. Investigations have shown that solar energy is a feasible heat source during the sunlit portion of the day, but electrical resistance heat may be required during night time and periods of low insolation.

Electrical heat pumps have been used as a replacement for resistance heating in low temperature drying. Because of the coefficient of performance of a heat pump, it is possible to get from 2 to 4 kilowatt hours of heat energy for every kilowatt of electrical energy consumed at typical ambient air conditions present during the corn drying season. Thus, when resistance heating is replaced by a heat pump, electrical energy requirements can be substantially reduced.

It appears feasible that solar energy supplemented by a heat pump could provide a fairly constant heat source. A constant drying potential could be maintained by using a solar collector as a heat source during periods of high insolation and by augmenting the collector with a heat pump during night hours and periods of low insolation. By effectively combining the two, significant energy savings could be realized.

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[1]Research Assistant, Agricultural Engineering, University of Illinois, Urbana, Illinois

[2]Professor of Agricultural Engineering, University of Illinois, Urbana Illinois

THE EXPERIMENT

The investigation was performed during the fall of 1975 and the fall of 1976 at the University of Illinois Agricultural Engineering Research Farm near Urbana, Illinois. Two different systems were studied during the investigation.

1975 SYSTEM -- The grain drying system consisted of a 211 m^3 (6000 bu), 7.32 m (24 ft) diameter bin equipped with a 7.46 kw (10 hp) centrifugal drying fan. Drying heat was provided by a 8.92 m^2 (96 ft^2) solar collector and a 17.58 kw (60,000 Btu/hr) heat pump.

The solar collector used in this study was a portable commercial unit manufactured by Solar-Aire Company (Fig. 1). It was a wheel mounted flat plate collector that could be tilted to the optimum collecting orientation. The absorbing surface of the collector was composed of closely spaced black aluminum cups. The collector had two fiberglass cover sheets to reduce convective heat losses through the collector face, and it was insulated to decrease conductive heat losses through the collector sides and back. An airflow rate of 0.165 m^3/sec (350 cfm) was supplied by a small electric blower mounted on the collector. The solar warmed air exited the collector through a 20.32 cm (8 in) diameter flexible exhaust tube (Fig. 2). During the entire drying experiment the collector was oriented to the south with a slope of 60 degrees.

The heat pump used in the system was a 17.58 kw (60,000 Btu/hr) General Electric single package air-to-air unit currently available for home heating application (Fig. 2).

The heat pump and collector were combined in an attempt to provide a reasonably constant drying potential of 3 C (5.4 F) by using solar energy to heat the drying air during sunshine hours and the heat pump during the night and periods of low insolation. This constant potential was controlled by a differential thermostat, a thermostat that functions on temperature differential detection between two sensing points. When the solar collector could provide enough solar heat to create a 3 to 4 C (5.4 to 7.2 F) temperature differential between the bin plenum and ambient air, the heat pump power circuit was held in an open position by the thermostat. When solar heating was insufficient to supply at least a 1 C (1.8 F) differential, the thermostat would close the heat pump power circuit to provide additional heat.

1975 RESULTS -- The drying period ran 34 days from October 21 to November 24. During this time 211 m^3 (6000 bu) of shelled corn were dried from an initial moisture content of 20.7% to a final moisture content of 15.2% (wb).

Data taken on November 22, a sunny day, was used to evaluate collector performance (Table 1). On this day, a peak temperature rise of 26.7 C (48.1 F) occurred at 1:00 p.m. The average temperature rise over the sunlit portion of the day was 18.2 C (32.7 F), with a total energy collection of 33.21 kWh (113,000 Btu).

Table 1. Collector Performance for November 22, 1975

Time	Temperature Rise Through Collector, C	Energy Collected, W	Collector Efficiency, %
8:00	1.7	345	15.0
9:00	12.8	2598	36.6
10:00	16.9	3431	44.8
11:00	24.7	5014	64.6
12:00	25.8	5237	61.7
1:00	26.7	5420	67.3
2:00	23.9	4852	63.3
3:00	19.4	3938	62.0
4:00	11.7	2375	02.7

Total Daily Energy Collected -- 33.21 kWh
Total Daily Collector Efficiency -- 57%

The drying potential created when the solar heated air was mixed with the total volume of air moved by the drying fan (4.48 m^3/sec (9500 cfm)) was a maximum of 1 C (1.8 F) during the peak collecting hours of 10:00 a.m. to 2:00 p.m. Another 1 C to 2 C (1.8 F to 3.6 F) of drying potential was created from the turbulent mechanical action of the fan moving the air; thus the total drying potential created by the fan and collector was 2 C to 3 C (3.6 F to 5.4 F) during the prime collecting hours on a sunny day. The average drying potential created by the collector over the sunlit portion of the day determined by an energy balance between the collector and fan airflow was 0.67 C (1.2 F) for the cloudless day of November 22; thus the actual drying potential created by the collector was relatively small.

During the drying period the heat pump operated 327.6 hours or approximately 40% of the time. The solar collector did not produce a sufficiently large enough drying potential for the differential thermostat to effectively sense; hence the amount of solar energy collected had little influence on the heat pump operation. Because of this, the thermostat was set to operate the heat pump in a cyclic fashion.

The heat pump had an average coefficient of performance of 2.3 between ambient air conditions of 0 C (32 F) and 10 C (50 F). The heat pump had a measured airflow of 1.06 m^3/sec (2250 cfm) and an electrical input power of 7.2 kW; thus its average heat output was 16.6 kW (56,300 Btu/hr). This heat output created an approximate drying potential of 3 C (5.4 F). When added to the potential created by the drying fan, a total drying potential of 4 C to 5 C (7.2 to 9 F) was available for drying.

The electrical energy usage for the 1975 experiment included 6629 kWh by the drying fan and 2359 kWh by the heat pump for a total of 8988 kWh. Energy usage by the small blower on the collector was disregarded. In terms of moisture removed from the corn the energy usage was 7.75 kWh/m^3/point of moisture removed (0.273 kWh/bu/point of moisture removed) or 0.885 kWh/kg of water removed (0.388 kWh/lb of water removed).

1976 SYSTEM -- The same 211 m^3 (6000 bu) bin, 7.46 kW (10 hp) centrifugal drying fan, and the 17.58 kW (60,000 Btu/hr) heat pump used in 1975 were used for the 1976 drying experiment. To increase the quantity of solar energy available for drying, two new larger collectors were constructed.

The collectors constructed for the 1976 study were a covered plate and a bare plate collector (Fig. 3). Each collector had 26.76 m^2 (288 ft^2) of collecting area and both were oriented to the south with a collector face slope of 60 degrees.

The cover sheet for the covered plate collector was clear, corrugated, Tedlar-coated fiberglass. The absorbing surface of the collector consisted of black-painted 1.27 cm (1/2 in) thick plywood. Air entered the collector at the top, was heated as it was drawn between the absorber plate and the cover sheet, and was discharged through a .610 (2 ft) diameter duct in the collector back.

The bare plate collector was identical to the covered plate collector with the exception that the fiberglass cover sheet was replaced with black-painted corrugated steel roofing sheets. The roofing sheets functioned as the solar absorbing surface with air being heated convectively from the solar warmed roofing sheets as it was drawn between the roofing sheets and the plywood.

Both of the collectors and the heat pump were ducted to a plywood ducting box (Fig. 4) connected to the centrifugal drying fan so that all the airflow through the collectors was provided by the drying fan.

The mode of operation for the 1976 experiment was altered somewhat over that used in 1975. Because of problems encountered from the use of a differential thermostat in controlling heat pump operation, the use of the thermostat was discontinued in 1976 and the heat pump operation was regulated by a time clock. Solar energy was used exclusively for providing drying heat during the daytime, and the time clock operated the heat pump ten hours during the night to provide a drying potential for nighttime drying.

1976 RESULTS -- The grain drying period ran 33 days from October 15 to November 17. During the period 201 m^3 (5700 bu) of shelled corn were dried from an initial moisture content of 22.3% to a final moisture content of 15.0% (wb).

Data taken on November 7, a sunny day was used to evaluate collector performance (Table 2). On this day, a peak temperature rise of 8.4 C (15.1 F) occurred through the covered plate collector and a peak rise of 6.4 C (11.5 F) occurred through the bare plate collector. The average temperature rise over the sunlit portion of the day was 5.6 C (10.1 F) through the covered plate collector and 3.9 C (7.0 F) through the bare plate collector. An airflow rate of 1.982 m^3/sec (4200 cfm) was measured through the exhaust ducts of each collector. A total daily energy of 121.7 kWh (415,300 Btu) was collected by the covered plate collector and 84.3 kWh (287,600 Btu) was collected by the bare plate collector, resulting in a total daily efficiency of 70.9% for the covered plate collector and 49.1% for the bare plate collector. This collector heat created an average drying potential of 3.6 C (6.5 F) over the sunlit portion of the day. With the addition of the 1 C (1.8 F) potential delivered by the mechanical action of the drying fan, the average potential available for drying was 4.6 C (8.3 F).

Table 2. Collector Performance for November 7, 1976

	Covered Plate Collector		Bare Plate Collector	
Time	Temperature Rise, C	Energy Collected, W	Temperature Rise, C	Energy Collected, W
8:00	2.9	7000	1.0	2420
9:00	5.5	13280	3.8	9180
10:00	6.9	16660	5.0	12080
11:00	7.9	19080	5.6	13520
12:00	8.4	20290	6.4	15460
1:00	7.2	17390	5.1	12320
2:00	6.1	14730	4.2	10140
3:00	4.0	9660	2.8	6760
4:00	1.5	3620	1.0	2420

Total Daily Energy Collected (Covered Plate Collector) -- 121.71 kWh
Total Daily Energy Collected (Bare Plate Collector) -- 84.30 kWh
Total Daily Efficiency (Covered Plate Collector) -- 70.9%
Total Daily Efficiency (Bare Plate Collector) -- 49.1%

Because of the large amount of heat energy made available by the collectors for drying, the heat pump was only operated 10 nights for 10 hours each night during the middle of the drying season. The performance characteristics and airflow rates of the heat pump were the same in the 1976 experiment as in the 1975 investigation.

The electrical energy usage for the 1976 experiment included 5970 kWh by the drying fan and 720 kWh by the heat pump for a total of 6690 kWh. In terms of moisture removed from the corn the energy usage was 4.57 kWh/m^3/point of moisture removed (0.161 kWh/bu/point of moisture removed) or 0.494 kWh/kg of water removed (0.224 kWh/lb of water removed).

SUMMARY

The solar collector -- heat pump combination effectively reduced the electrical energy requirements for the low temperature drying of shelled corn from the accepted value of 8.51 kWh/m^3/point of moisture removed (0.3 kWh/bu/point of moisture removed) (Shove, 1976). The 8.92 m^2 (96 ft^2) portable collector used in 1975 was too small to be effectively used on a 211 m^3 (6,000 bu) bin equipped with a 7.46 kW (10 hp) fan; thus the energy reduction was small for the 1975 investigation. But the 1976 collectors along with the heat pump provided a sufficient amount of heat energy to almost halve the electrical consumption required for low temperature drying.

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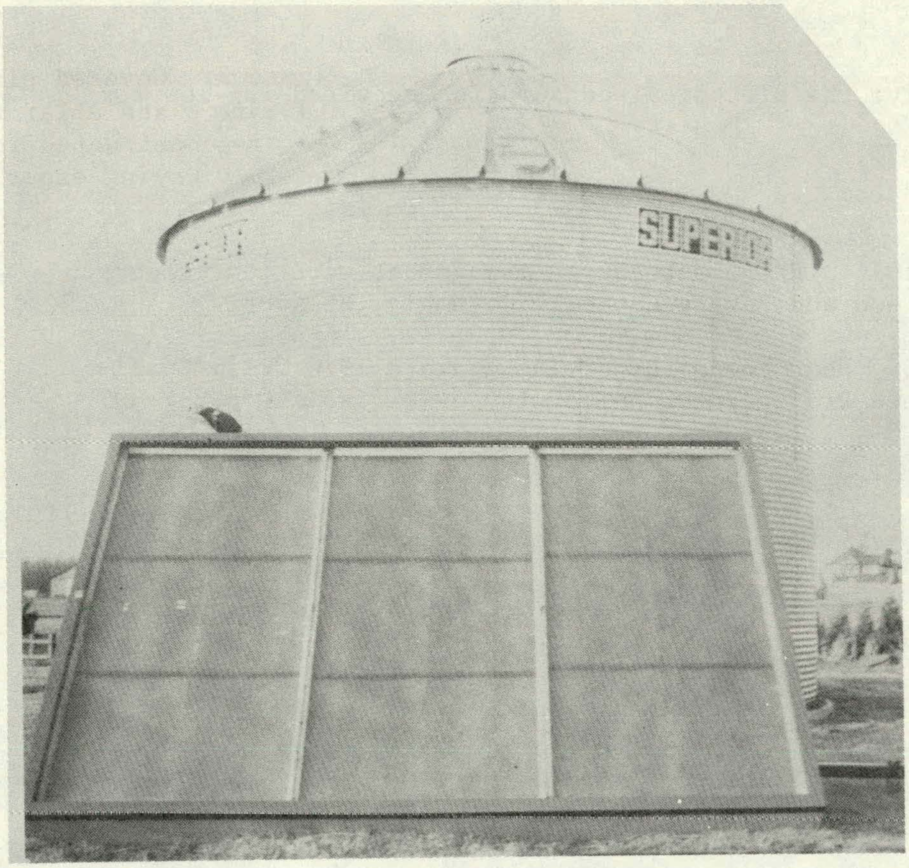

Figure 1. Portable solar collector used in 1975 solar energy-heat pump grain drying experiment.

Figure 2. Flexible duct used to duct heated air from solar collector to drying fan and 17.58 kW heat pump used in the experiment.

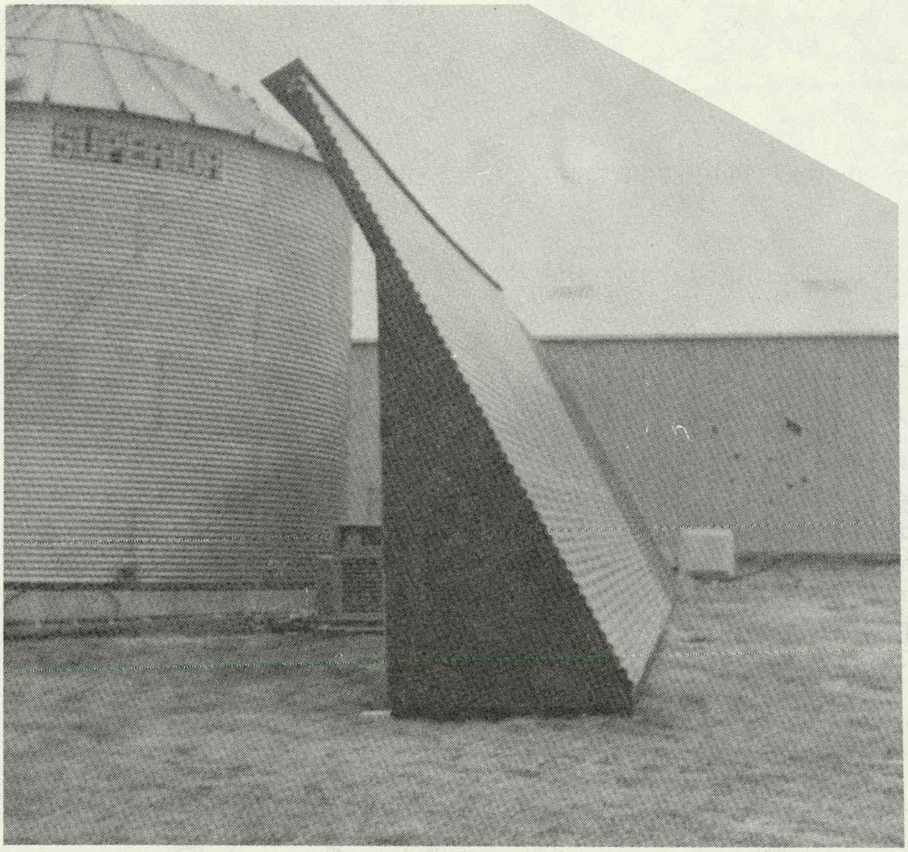

Figure 3. Covered plate and bare plate solar collectors constructed for the 1976 drying experiment.

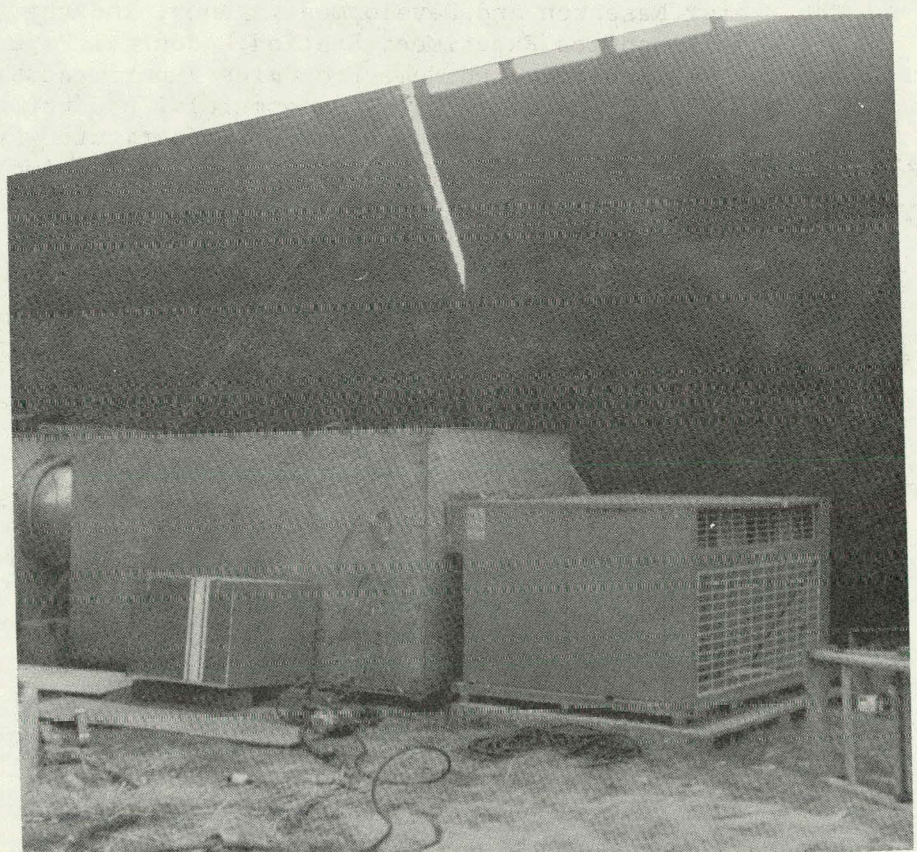

Figure 4. Plywood ducting box into which the heat pump and solar collectors were ducted.

SOLAR-ASSISTED HEAT PUMP FOR LOW-TEMPERATURE CORN DRYING*

Michael E. Anderson and Carl J. Bern[1]

INTRODUCTION

The heat pump is a device capable of transferring heat from one place to another in a refrigerant fluid. Heat pumps are being used to heat drying air in low-temperature corn-drying systems, Wilson (4). Utilization of a solar energy input can, under certain conditions, improve the energy utilization efficiency of the heat pump. This paper reports on field tests of a low-temperature corn-drying system using a solar-assisted heat pump.

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[1]Research Associate and Associate Professor, Agricultural Engineering Department, Iowa State University, Ames, Iowa.

HEAT PUMP OPERATION

Heat pumps for home use can transfer heat from the air within the house to the air outside the house for summer cooling and, after appropriate changes in refrigerant valve position, can transfer heat from outside air to air within the house for winter heating. Figure 1 illustrates operation of a heat pump for a heating application. In this heating mode of operation, the indoor heat-exchanger coil is the condenser, and the outdoor heat exchanger is the evaporator in the refrigerant cycle. The Coefficient of Performance (COP) of the heat pump is the ratio of the energy input into the compressor to the energy output from the condenser. A heat pump operating at COP of 3.0 is, then, delivering 3 units of energy (heat) from the condenser for every unit of energy (electricity) delivered to the compressor. If the input air temperature to the condenser is held constant, the COP increases with increasing evaporator air temperature. The heat pump output also is increased in this same manner, as seen in Figure 2, General Electric (1).

If the input air stream to the heat pump evaporator is heated by a solar collector, the COP of the heat pump will be increased. A portable solar collector, in combination with a package-system heat pump offers a potential for electrical energy savings over electrical-resistance heat or a heat pump alone. Such a system can be used for low-temperature grain drying, as well as for home or farm building heating applications.

DRYING EXPERIMENTS FOR FALL 1976

Two 3300-bu (87-tonne), 18-ft. (5.5-m) diameter grain bins were filled with corn and low-temperature dried. One bin was equipped with a 24,000-BTU/hr (7034-W) GE model BGWC024A, Figure 2, package-system heat pump in combination with two suspended-plate solar collectors. The heat pump delivered heated air into the flow of the grain-drying fan. A second (control) bin used 2.4kW of electrical resistance heat and was used as a comparison for energy and cost. Each bin used a 5-HP (3.7-kW), 24-in. (0.61-m), axial-flow fan.

Figure 3 shows the experimental apparatus. The two solar collectors were designed and built by using criteria from pilot-model solar-collector results, Kline (3):

TYPE	- COVERED, SUSPENDED PLATE
DESIGN TEMPERATURE RISE (max)	- 20°C (36°F)
DESIGN AIRFLOW	- 25.5 m^3/min (900 cfm)
DESIGN EFFICIENCY (overall)	- 50%
MOUNTING ANGLE	- 45° FROM HORIZONTAL
ABSORBER SURFACE AREA	- 23.8 m^2 (256 ft^2)
CROSS-SECTIONAL AREA	- 0.26 m^2 (2.83 ft^2)
COST OF MATERIALS	- \$40/m^2 (\$3.67/ft^2)
CONSTRUCTION TIME	- 3.9 (0.36) manhours/m^2 (ft^2)

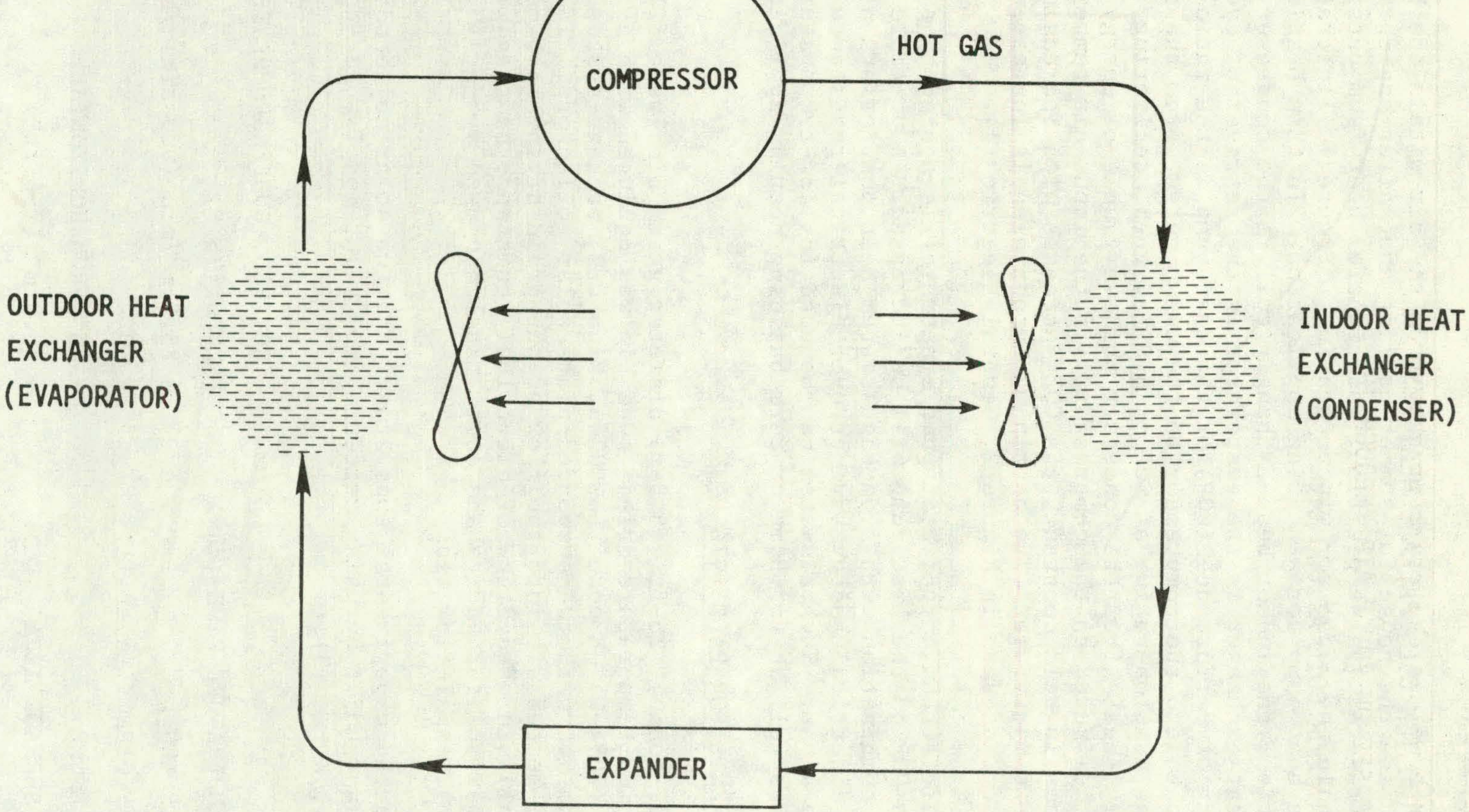

Figure 1. Heating Mode of the Heat Pump, KEMLER (2)

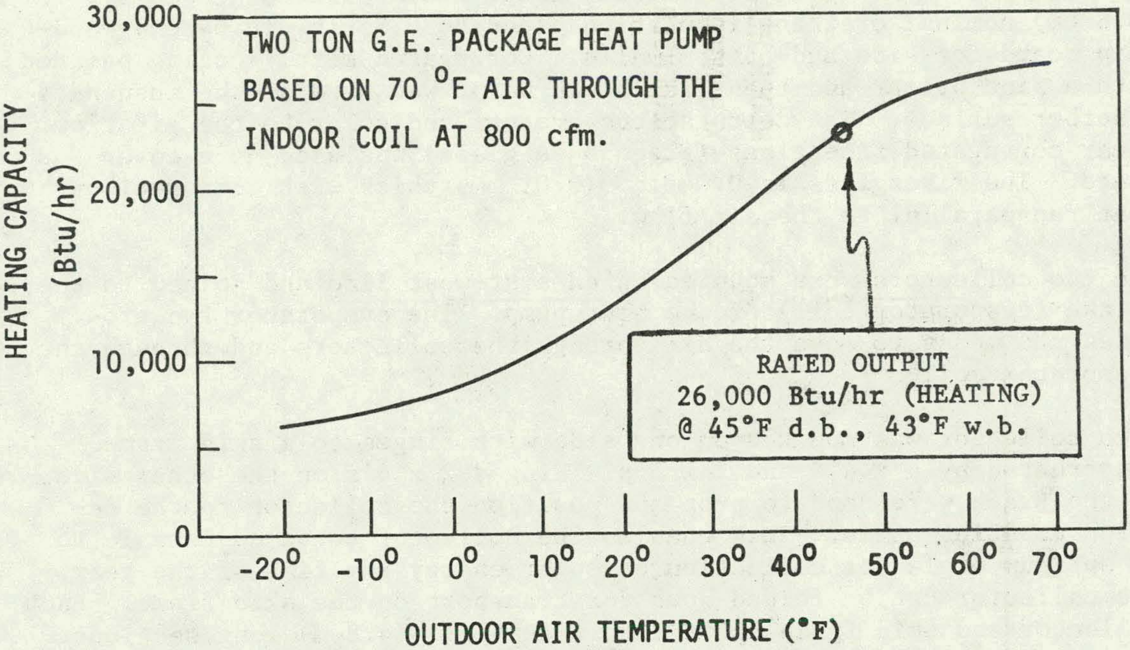

Figure 2. Heating Capacity vs Outdoor Air Temperature.

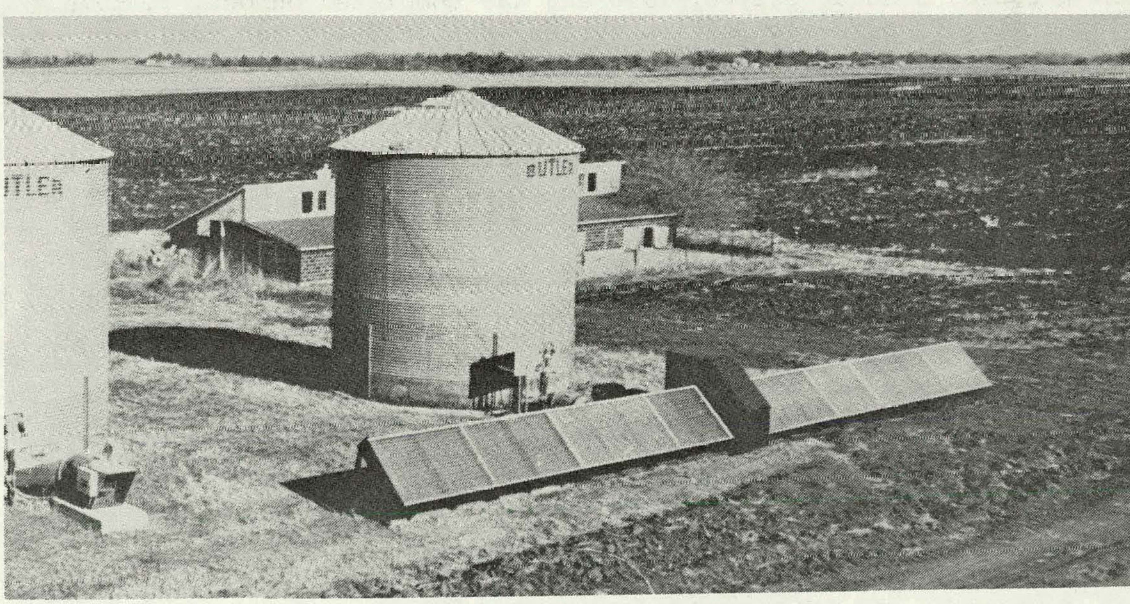

Figure 3. Experimental Apparatus.

Each solar collector was constructed with a rectangular cross section, 4 ft. (1.2 m) wide by 32 ft. (9.6 m) long. The collectors used 1.5-in. (3.8-cm) nominal urethane insulation glued on 0.25-in. (0.64-cm) wood-chip board for side and bottom walls. Corrugated metal roofing painted with a zinc primer and then flat black paint was used as the suspended absorber surface. The corrugations are perpendicular to the air flow. Clear corrugated fiberglass (greenhouse glass) was used as a cover plate. The fiberglass is 0.04 in. (0.01 mm) thick with corrugations that run parallel to the air flow.

The two collectors were mounted on an east-west line and joined to the intake (evaporator coil) of the heat pump. The evaporator fan provides the means to move the air through the collectors and through the evaporator coil.

Each collector was mounted on one side with hinges to a skid frame constructed by 4 x 4's and 2 x 6's. Hinged 2 x 4's on the other side of the frame were used to prop and position the collector to the desired mounting angle. This enables the collector to be adjustable to an optimum angle for collection of solar energy any time of the year. The collector can be folded down for transport on the skid frame. Each collector and skid frame split into two 16-ft. (4.8-m) long sections for ease of transport. Clothesline wire was looped through holes drilled in the ends of the 4 x 4's for towing by tractor and chain. The 4 x 4 skid frame permits transportation around the farm.

TESTING PROCEDURE

Filling the bins began Oct. 6, 1976 and was completed on Oct. 7, 1976. During drying, a data-acquisition system monitored and recorded temperatures of the solar-collector output air, the heater output air, the bin input air, the heat pump output air, and the ambient air. The solar radiation intensity was monitored by a solar pyranometer and recorded by the data acquisition system. Watthour meters were used to measure electrical energy input to the electric heater, the heat pump, and each of the drying fans.

Drying progressed until corn at the top of the bin was 15% wet basis. The grain condition is summarized in Table 1.

OPERATION SCHEDULE

Matching the output of the electrical resistance heater and expected output of the heat pump, the following schedule of operation was used:

OPERATION SCHEDULE

	CONTROL BIN	SOLAR-ASSISTED-HEAT-PUMP BIN
DRYER FAN	continuous	continuous
HEATER (2.4 kW)	continuous	________
HEAT PUMP AND SOLAR COLLECTOR	________	8:30 A.M. to 5:30 P.M.

Figure 4 shows a typical sunny day of output versus time of day for the solar-assisted-heat-pump system. The average ambient temperature from 8:30 to 5:30 was 53°F (11.8°C). The peak output from the solar collector was 27,800-Btu/hr (8.2 kW). Peak output from the heat pump was 53,000-Btu/hr (15.7 kW). (The heat pump is rated at 24,000-Btu/hr (7 kW) with 70°F air entering the evaporator and 45°F air entering the condenser. See Fig. 2)

ENERGY

Some figures on the electrical energy consumed in both bins are shown in Table 2. The solar-assisted-heat-pump used about 15% less electrical energy per bushel to dry corn than did the control bin. The drying fan consumed a larger portion of the total electrical energy in the solar-assisted-heat-pump bin than in the control bin.

SOLAR COLLECTOR COSTS

Construction costs for the collectors which were built at Iowa State University were:

Materials:	\$367/100 ft^2
Labor (\$6/hr):	\$206/100 ft^2
	\$513/100 ft^2

CONCLUSION

The solar-assisted-heat-pump system performed according to theory. The solar collectors increased the COP (and thus the output) of the heat pump at a given outside air temperature.

The solar-assisted heat pump system required less electrical energy to dry the grain than did the control bin. This also means that the electrical bill for grain dried with this solar-assisted-heat-pump system would be less than the bill for the same grain dried in a system like the control bin. Substantially less electrical energy was required in the solar-assisted-heat-pump system to remove a unit mass of water from the grain.

Currently, more analysis is being performed on the effectiveness of the solar-assisted-heat-pump system as compared to a heat pump alone. Heat pump performance at various condenser and evaporator operating air temperatures is being investigated for our information in the General Electric Research Center in Tyler, Texas.

Table 1 Grain Condition

	CONTROL BIN (2.4 kW Electric)	SOLAR-ASSISTED-HEAT-PUMP BIN
WET GRAIN QUANTITY	85 tonne (3335 bu)	91 tonne (3586 bu)
AVG. INITIAL MOISTURE CONTENT (w.b.)	24.3%	24.0%
AVG. FINAL MOISTURE CONTENT (w.b.)	13.4%	12.8%
FINAL TEST WEIGHT	60.5 lbs/bu	59.5 lbs/bu
FINAL GRADE	No. 1 Yellow	No. 1 Yellow
TIME TO DRY ; days	36	37
AIRFLOW RATE; m^3/min-tonne (cfm/bu)	1.4 (1.3)	1.3 (1.2)

Table 2 Electrical Energy Usage

	CONTROL BIN (2.4 kW Electric)	SOLAR-ASSISTED-HEAT-PUMP BIN
TOTAL ELECTRICAL ENERGY COST*	$2.40/tonne ($0.061/bu)	$2.03/tonne ($0.052/bu)
$/tonne - % point removed ($/bu-%)	0.22(0.0056)	0.18(0.0049)
kWhr/tonne - % point removed (kWhr/bu-%)	85.5(0.199)	72.3(0.175)
Btu/lb H_2O removed (kJ/kg)	1051(2444)	872(2028)
PERCENT OF TOTAL ELECTRICAL ENERGY CONSUMED		
FAN	74%	84%
HEATER	26%	--
HEAT PUMP	--	16%

* @ 2.81 ¢/kWhr

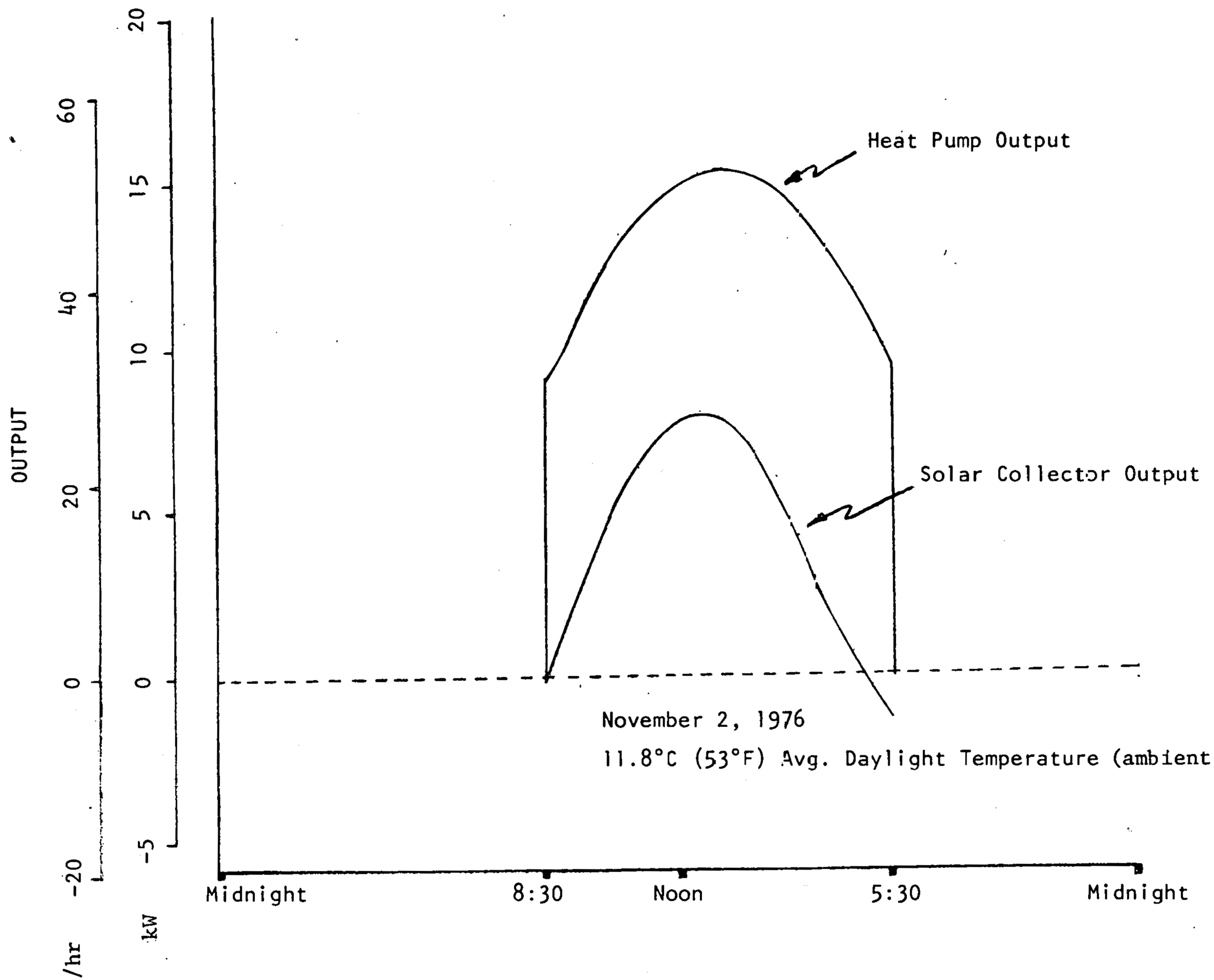

Figure 4. Solar collector and heat pump energy output vs. time.

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A SOLAR POND COLLECTOR AND HEAT STORAGE DEVICE

Ted H. Short, Warren L. Roller, Phillip C. Badger[1]

A solar pond is being studied as a solar collector and potential storage system along with the appropriate equipment to move heat from the pond to a greenhouse. The pond was designed to meet all of the winter heat requirements of a 186m^2 (2000 ft^2) three bedroom home or a 98m^2 (1000 ft^2) greenhouse in Wooster, Ohio. This system could also be applicable for process heating such as grain drying.

Natural solar ponds were first discovered in the early 1900's in Hungary as noted by Kalecsinsky (1902). Temperatures up to 80°C (176°F) have been recorded. It is theorized that such ponds are fed by saltwater springs while fresh rainwater periodically flushes off the surface. The result is a stable pond of solar heated brine at the bottom which is too dense to circulate to the surface and cool. More recently, researchers believe that a warm lake in Antarctica is a solar pond rather than a previously assumed hot spring lake (Angino, 1964). Tabor (1963) has probably done some of the most extensive work to date to make the solar pond economically useful for power generation in Israel. Israel is in a high radiation area and the Dead Sea is a good brine source. Tabor was able to achieve small pond temperatures up to 90°C (194°F), but had numerous technical problems with large ponds. One large pond in a marsh area was destroyed by mud bulges and gas bubbles being generated as the pond warmed. A plastic liner was subsequently installed, but the same bubble action lifted the liner in various areas and caused severe mixing of the pond. There were also tedious problems in establishing the pond concentration gradients and the research was essentially stopped. Rabl and Nielsen (1975) have studied the solar pond as a solution to space heating of residences in Ohio and similar areas. Rabl calculated that a pond equal in volume to a well insulated three bedroom home could meet all of the winter space heat requirements of that home. Nielsen (1975) further developed a unique salt gradient establishment procedure using a small pool and laboratory models.

Based on Rabl and Nielsen's work, a full-scale experimental solar pond was constructed adjacent to the Department of Agricultural Engineering greenhouse at the Ohio Agricultural Research and Development Center (Figure 1).

DESIGN AND ESTABLISHMENT OF THE SOLAR POND

The OARDC pond is 3.6 meters deep, 8.5 meters wide and 18.3 meters long (12 ft. x 28 ft. x 60 ft.). The pond walls are post and plywood construction with a sand bottom. Two 30 mil chlorinated-polyethylene liners with a nylon scrim were fabricated to fit the pit and contain the brine. The side walls

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[1]Ted H. Short, Associate Professor, Warren L. Roller, Professor and Phillip C. Badger, Research Associate, Department of Agricultural Engineering, Ohio Agricultural Research and Development Center, Wooster, Ohio 44691.

were insulated and the bottom is expected to become insulated as the warm pond dries out the surrounding soil.

The pond walls were designed to accommodate a standard "clear span" plastic covered greenhouse. The pipe frame for the cover is shown in Figure 2. This air-inflated double plastic cover was installed over the pipe frame to 1) help insulate the pond, 2) minimize dirt and trash contamination, 3) quiet the surface to reduce light scatter and gradient mixing, and 4) raise the humidity above the water surface to control evaporation. A reflector was designed for the inside north greenhouse wall to increase the effective collection area of the pond.

A 1.8 m (6 ft.) convective zone of approximately 20% salt (sodium chloride) was established in the bottom half of the pond. The top half has a concentration gradient that varies from 20% at the 1.8 m (6 ft.) depth to zero at the surface. This top section is non-convective (no circulation occurs) since the fluid density increases from the surface to the mid-depth of the pond.

The salt concentration gradient was established according to a technique developed by Nielsen (1975). The pond was filled to the three-quarter level with a 20% solution. Fresh water was carefully distributed over a floating sheet of plywood until the pond was full. The sizeable density difference of the freshwater and concentrated brine resulted in two distinct sections with little mixing. A pump with two inlets was then used to extract equal amounts of fluid from each section. The pump mixed the 20% solution with the freshwater to get a 10% solution. The 10% solution was injected between the original sections creating a new concentration zone occupying one-third of the top half of the pond. Subsequently, the three (0%, 10%, 20%) zones were used to form five zones (0%, 5%, 10%, 15%, and 20%) and the 5 zones were used to form nine final zones. The nine final zones were approximately 20 cm (8 in.) thick which was small enough for a perfect gradient to eventually form by diffusion and mixing.

RADIATION COLLECTION AND HEAT STORAGE

The solar pond is heated by solar radiation passing through the saltwater to the black liner holding the liquid. As the black liner temperature increases, heat is transferred to the 20% brine in the bottom half of the pond. The heated 20% brine rises no higher than the bottom layer of the gradient and cooler 20% brine moves down to replace it. The upper non-convective region is nearly transparent to incoming ultra-violet and visible radiation and nearly opaque to incoming infra-red and outgoing long-wave re-radiation. One meter (39.5 in) of non-convective water is a good insulator with a conductivity equivalent to approximately 6 cm (2.4 in) of styrofoam. Since the walls are also insulated, losses are reduced significantly.

A major advantage of the solar pond is that both summer and winter radiation can be collected and stored for later use. After a full summer's radiation, the pond temperature throughout the bottom half could conceivably approach boiling. The limitation of the OARDC pond is 80°C (180°F) to maintain liner stability. This upper temperature limit may be controlled with discharge heat exchangers or by covering the pond with an opaque film.

RESULTS

Salt concentration profiles for three periods since construction can be seen in Figure 3. The July 23, 1975, profile was taken soon after the gradient was established. A number of locations of constant concentration illustrate the nature of the stepwise gradient. The horizontal portions of the curves are essentially convective zones. By September 3, 1975, the stepwise gradient had diffused into a nearly perfect gradient in the top half of the pond. A strong gradient between the depths of 40 and 200 cm still existed on January 22, 1976. However, salt diffusion and wind induced mixing had formed a convective zone at the surface. The brine depth had been reduced by surface evaporation and a small leak in the pond bottom that was repaired in March, 1976.

The gradient has required little maintenance since establishment. Salt diffuses very slowly from the more concentrated brine at the bottom to the less concentrated brine at the top. The diffusion rate in the OARDC pond has been calculated to be 726 kg (1600 lb.) per year. For maintenance, brine is flushed off the surface and freshwater added approximately every six months. This maintenance technique has been most successful with a cover over the pond. Wind can sometimes keep the surface mixed more than desired.

The temperature profile on three different dates can be seen on Figure 4. The maximum temperature of the pond has been 45.5°C (114°F) on September 16, 1975. This maximum was below the desired 82°C (180°F) and may have resulted from heat lost in drying out the soil under and around the pond. Actual collection efficiencies and various modes of heat loss are receiving further evaluation to explain the temperature responses. It should be noted that the temperature profile is very similar to the concentration profile especially after periods of cloudy weather.

The changes in maximum pond temperature can be seen in Figure 5 in relation to weekly radiation and average outside temperature. The pond temperature did not fluctuate as much as the radiation and outside air temperatures, but each factor had a similar trend line. The pond temperature in late August was limited by reduced radiation and a polyethylene film put on the surface to keep out debris and dirt from construction work neat the site. Much debris and algae growth collected on the film surface and the pond temperature remained constant. The average pond temperature had been gaining approximately 0.5°C (1°F) per day prior to covering. The pond was subsequently covered with a greenhouse structure in November, 1975, resulting in a reduction in pond temperature fluctuations. The overall effect of the greenhouse is being studied.

The soil temperature below the pond was monitored in relation to the bottom pond water temperature and a reference soil temperature equivalent in depth to the pond bottom (Figure 6). In the first year of operation, the soil beneath the liner was not heated enough to dry out and was highly affected by the pond temperature. Cooling occurred in all measured locations as the average outside air temperature decreased. There should be less cooling under the pond in future years, however, if the pond functions as planned.

There are still numerous questions to be answered concerning the feasibility of the solar pond as a heat storage device. The first real test of heat extraction is planned for 1977. Pond stability at high temperatures will be tested and evaluated. If all collection and heat transfer processes prove feasible, pond construction integrity may become one of the most critical factors. Solar ponds must be leakproof or be constructed to handle leaks that may occur at any time. Any leaks result in the pond losing both hot brine and dry soil insulation. Likewise, leaking brine may seriously contaminate surrounding water sources and soils. Currently, almost all ponds or pools leak or can be expected to leak at some time. There are no consistently effective ways of identifying and patching brine source leaks without draining the pond. Such problems, however, may be solved with new liner technology.

Other problems observed in constructing and operating open ponds are: 1) wind will cause surface mixing, 2) rain water must be removed after storms and water must be added to make up evaporative losses and 3) organic debris such as leaves will get blown into the pond. Leaves are buoyant at approximately 75 cm (30 in) below the surface. These leaves can interfere with light transmission for three to four months before sinking to the bottom.

Much more is yet to be learned about solar ponds. The potential is exciting - the unanticipated problems are frustrating and often costly. The net result will hopefully be an acceptable and economical solution to the collection, storage and utilization of solar energy for process or space heating.

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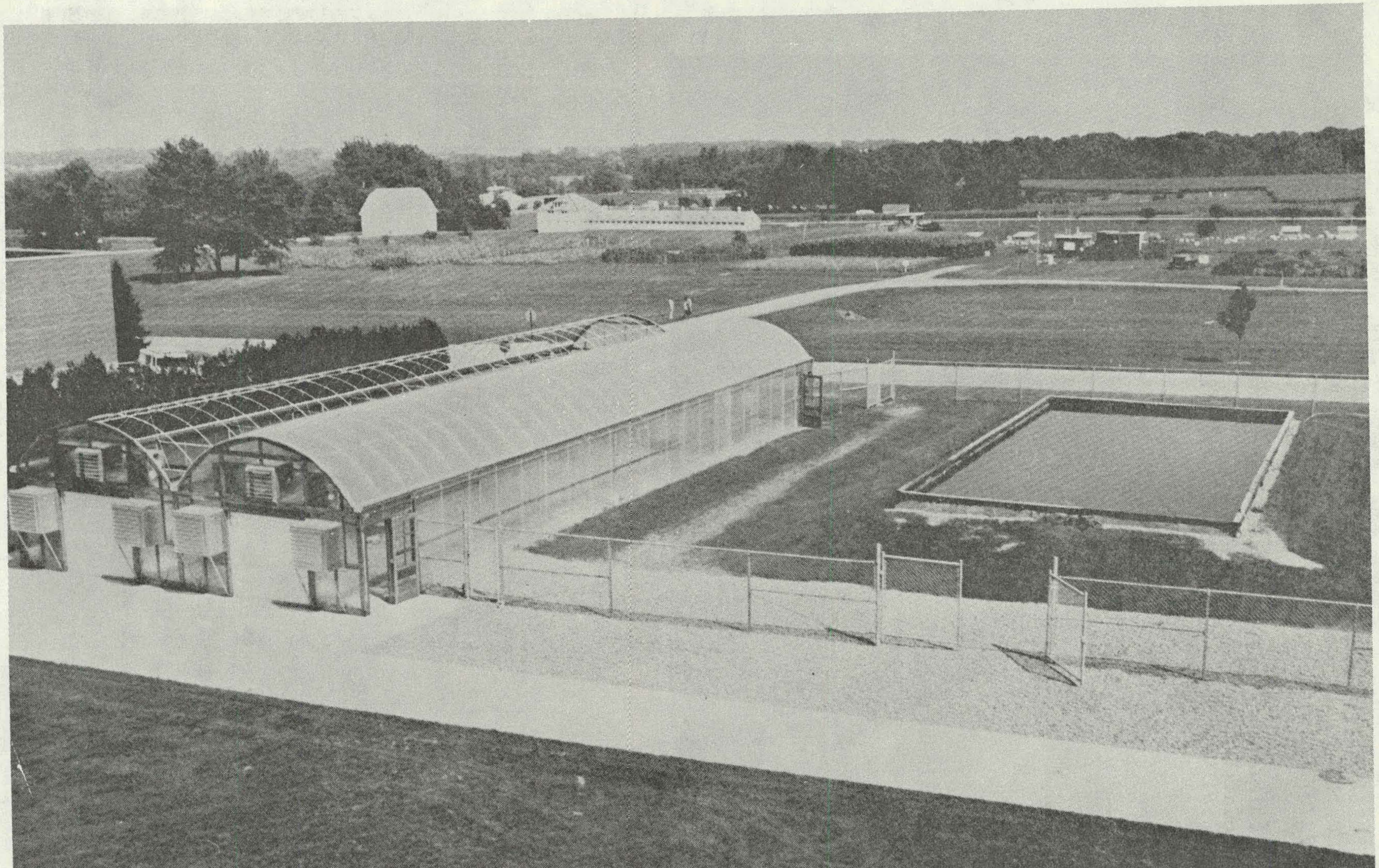

Figure 1. The solar pond is shown to the right of the two-module Agricultural Engineering greenhouse. Heat from the pond will be discharged in the covered and nearest greenhouse module. The adjacent module will be covered and heated conventionally.

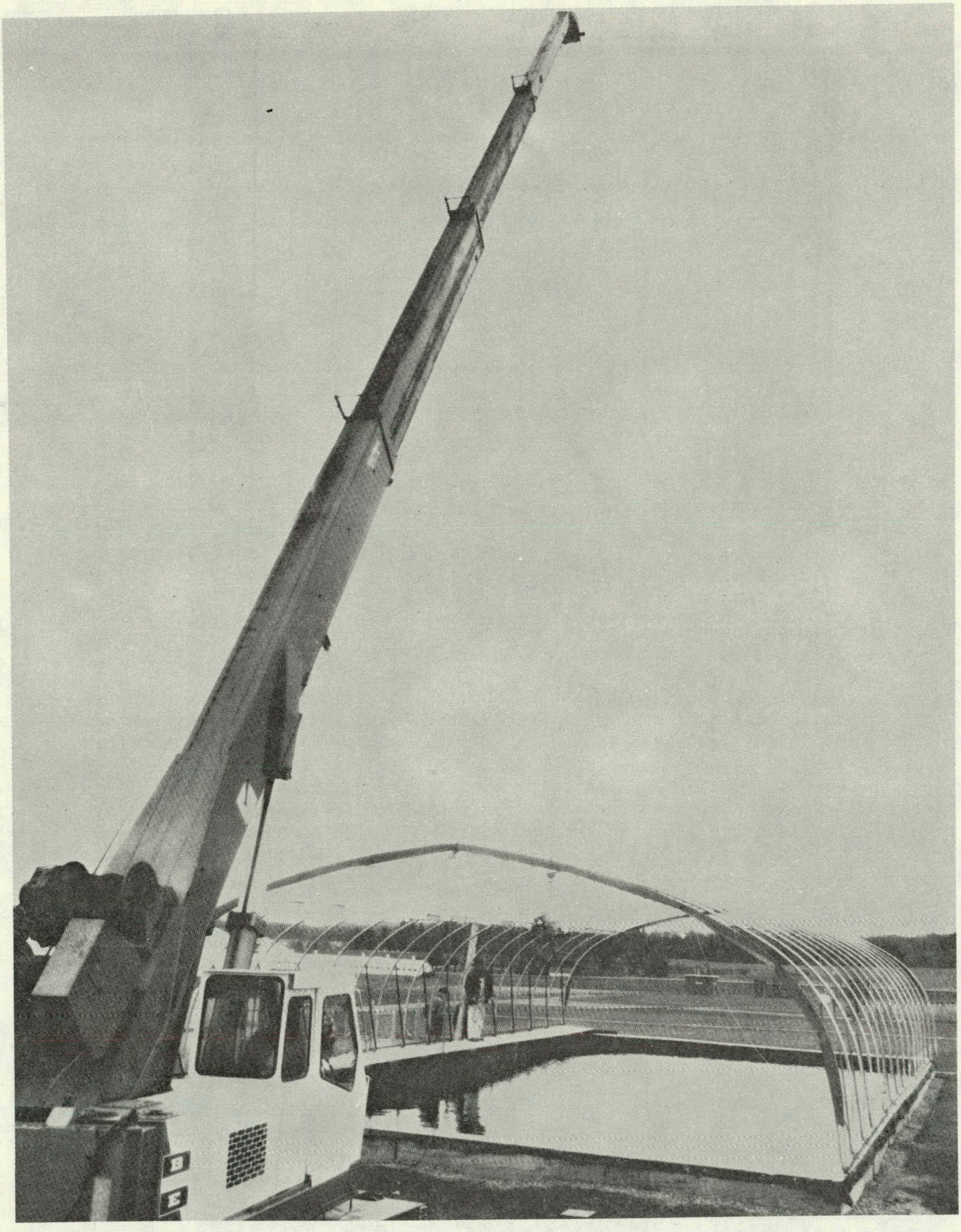

Figure 2. A pipe-frame is being erected on the solar pond to support clear plastic covers. The covers can help insulate the pond, prevent the inclusion of debris, and prevent surface mixing by wind.

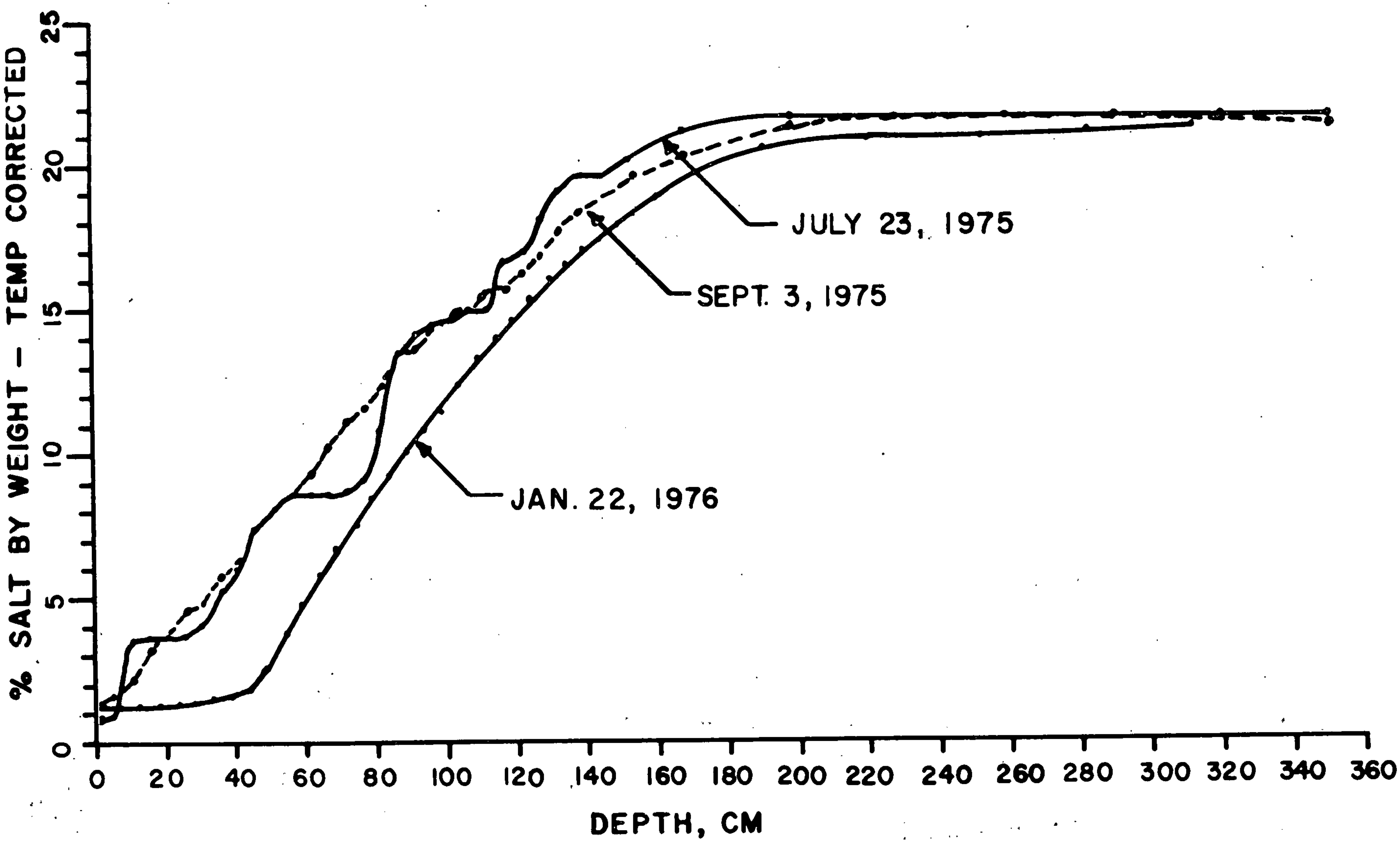

Figure 3. Solar pond concentration profiles for three different dates after pond establishment.

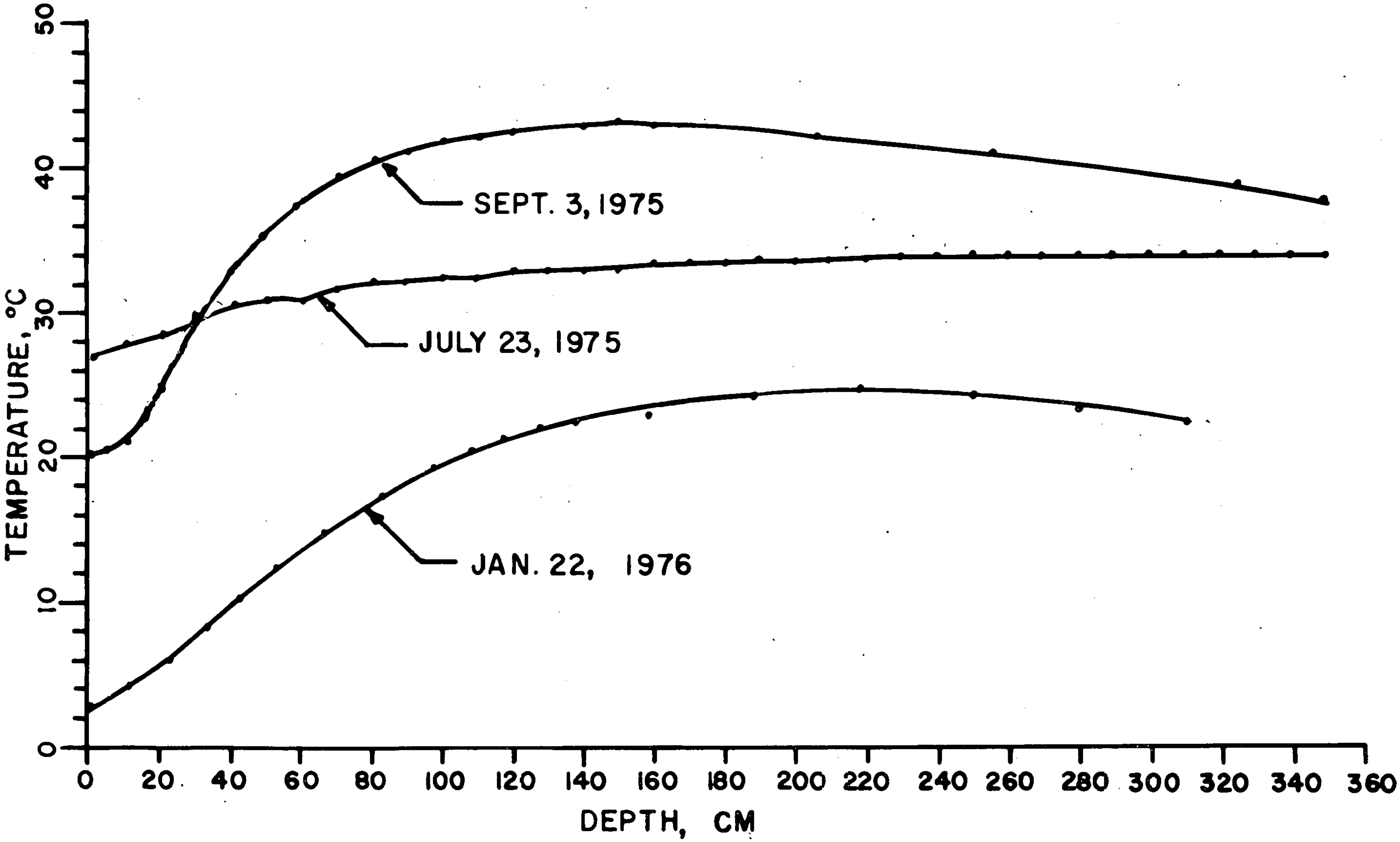

Figure 4. Solar pond temperature profiles for three different dates after pond establishment.

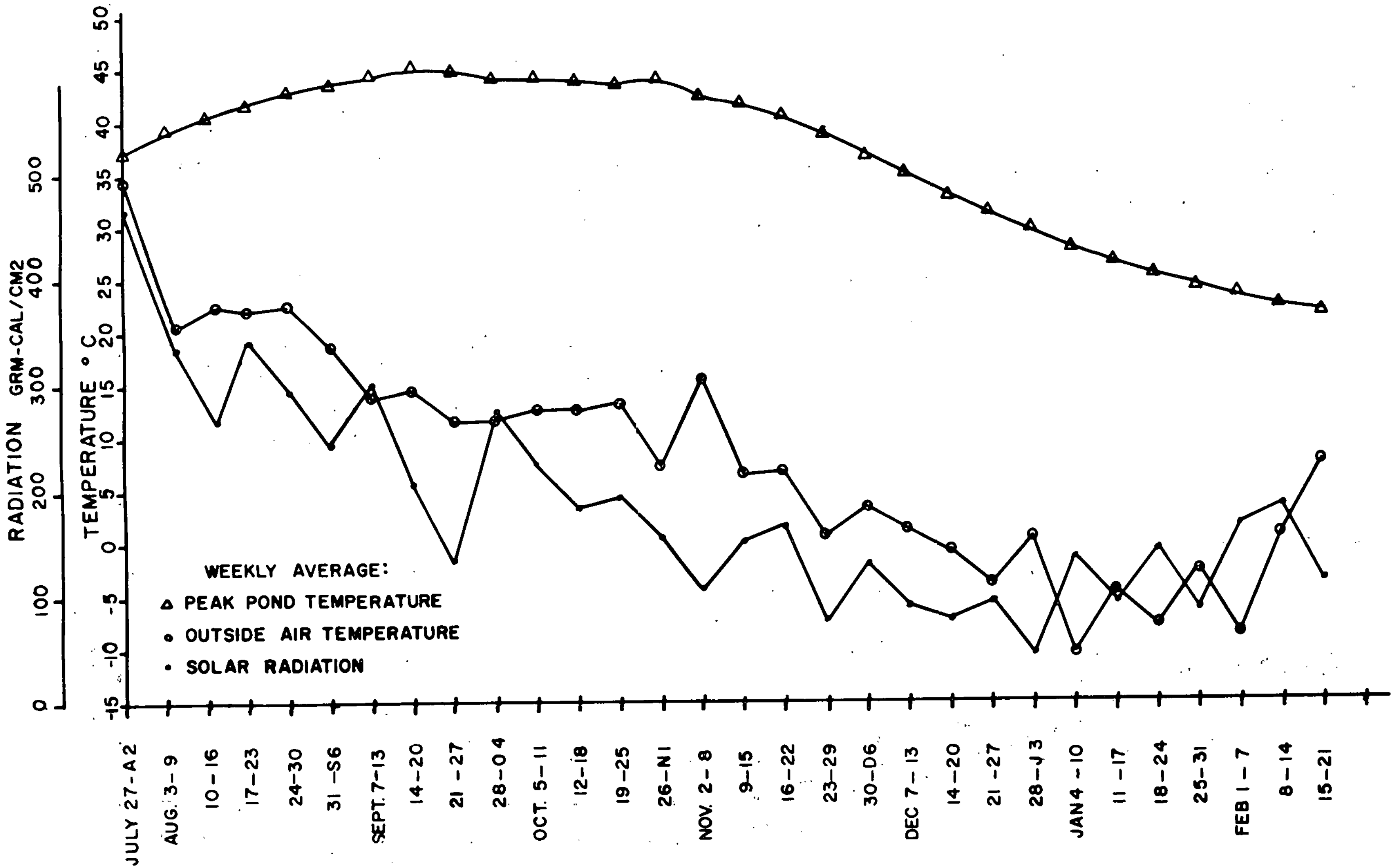

Figure 5. The effect of outside air temperature and solar radiation on peak pond temperature.

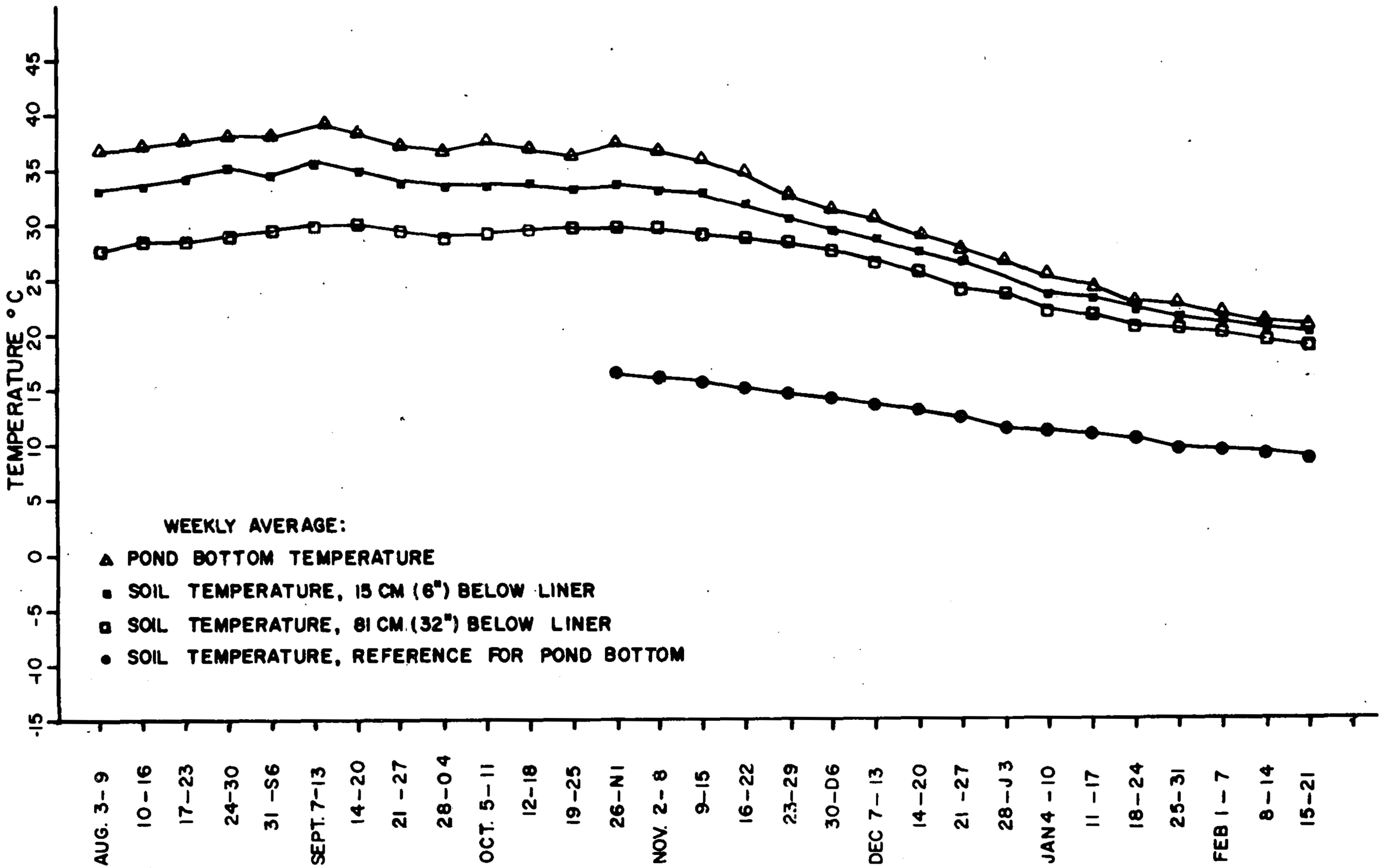

Figure 6. The relationship of soil temperatures below the pond to a reference soil temperature at the same depth as the pond bottom.

THERMAL STORAGE IN GRAIN DRYING

Steven R. Eckhoff and Martin R. Okos[1]

Technological advancements in the last twenty years have brought about many changes in accepted farming practices. One of the most noticeable has been the change from ear corn harvest and storage to shelled corn methods. Although the artificial drying associated with shelled corn harvest requires large amounts of energy, the overall harvest is a more efficient one. Ear corn occupies twice the storage space for the same amount of grain, naturally ventilated cribs are open to rodents, the harvest and handling equipment used is bulkier and more expensive, and the system has higher field losses. In addition, ear corn harvesting is more weather dependent, since greater emphasis is placed on field drying.

The energy shortage our country is experiencing has shown that the presently accepted high temperature drying associated with shelled corn handling may quickly become obsolete. Note that this obsolescence is not due to advancing technology, as was the case with ear corn harvesting, but rather is a result of dwindling fuel reserves. As a consequence there has been much investigation into the feasibility of natural air and solar supplemented grain drying procedures as a low energy replacement for high temperature drying. Research work has shown that drying with natural air and solar heated air is practical in the Midwest (1,2),but that it has an inherent problem in the unpredictability of the ambient air temperature and of the direct solar radiation available during the drying period.

The ability of a crop drying system to work satisfactorily in all situations without spoilage is important. Natural or solar grain drying cannot be satisfactory for just 9 out of 10 years or even 19 out of 20 years; it must be satisfactory every year. This is necessary because it is impossible to determine the year when the system will fail until the grain has already reached a critical situation demanding high temperature drying. Fuel might be available for a few dryers in such an emergency but the demand would be too great to supply a large area on such short notice.

Technology for natural air and solar grain drying systems must be developed to a level which eliminates the need for a backup drying system and is as reliable as the existing high temperature systems. The purpose of this paper is to investigate how thermal energy storage can be used for in-bin grain drying to enhance the drying confidence.

THERMAL STORAGE IN DRYING

There are two concepts for utilizing thermal storage in solar grain drying: long term and short term storage. Long term thermal storage would make available in the fall solar energy from the summer. Such a storage facility would be charged during the summer by means of solar collectors operating at low air flow rates and high temperatures. The stored energy could then be used in the fall as needed for drying.

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[1]Graduate Assistant and Assistant Professor, Agricultural Engineering Department, Purdue University, W. Lafayette, Indiana.

A long term storage facility would by its nature be very large and hold a large amount of heat. The actual amount of storage material needed would depend on the particular material used and the size of the associated grain drying facility. One characteristic of long term storage is that the storage temperature can be much higher than the normal efficient operating temperature of a solar collector. Concentrating collectors could charge the storage to even higher temperatures. High temperatures are advantageous for specific heat storage materials since the storage volume needed decreases as the charging temperature increases.

The initial cost of a long term storage facility might at first appear prohibitive, but such a large storage system allows much flexibility when considered as part of a total farmstead solar utilization system. Other possible uses for solar energy on the farm such as heating livestock ventilation air, space heating for shop and home, and water heating, help spread the cost over more operations and time. The storage device could be a large central facility heated by solar collectors from each of the separate applications or several smaller storage facilities could be used if all were available for use during grain drying.

Alternatively, a thermal storage device could be used for short term storage. Short term storage would store heat normally available only during the day for use at night. There are many different modes of operation for a short term storage system, but unless a second solar collector is used to heat the storage during the day, only a minimal gain in total energy would be available for drying grain. This gain would be due to the temperature difference between the average daytime ambient air and the average night time ambient air, but the difference is usually small. According to the Purdue Climatology Department, the average temperature difference between the daily high and the daily low for October and November in West Lafayette, Indiana is only about 20°F. The average temperature difference for the day would be on the order of only 10°F. Such a low temperature differential would require a very large storage volume to store an appreciable amount of energy.

Some researchers feel that damping the temperature flunctuation between day and night offers an advantage in preventing rewetting of the grain during the night. This may be a valid use for thermal storage but the same result may possibly be accomplished more inexpensively with the use of a timer to turn the bin fan off in the evening. Moderation of the temperature variation also appears to make poor use of the collected solar energy. The specific heat of air is fairly constant over the typical range of ambient air temperatures so that the enthalpy change in the air when it is raised from 45°F to 55°F is nearly equivalent to the enthalpy change when the air is raised from 70°F to 80°F. It can be seen from a psychrometric chart that while the change in enthalpies are equivalent, the drying potential of the warmer air is twenty percent greater. This would indicate that it is more efficient to use the collected solar energy during the day than at night when the ambient air temperature is lower.

Of the two uses for thermal storage in drying, long term storage seems to be the most practical choice. Long term storage offers independence from the day to day weather problems that could hinder the effective use of a short term storage. Just the assurance that there is heat available for drying before the grain is harvested gives the farmer a better opportunity to make good management decisions.

SOIL STORAGE

The thought of using soil as a heat storage medium is nothing new. During the early work with heat pumps in the 1940's and 1950's, soil was considered a possible heat source for the evaporator coil since the natural diurnal cycle would add heat back into the soil (3,4,5). A major problem arose with this use when ground water, which flows from warm areas to cool areas, caused the heat transfer pipes to freeze, preventing sufficient heat transfer. This freezing problem prevented further consideration of soil as a storage medium.

The opposite problem occured when researchers proposed using waste heat from processing and power plants to heat nearby farm land (6,7). The researchers found that when heat was applied, ground water would flow away from the heat transfer pipes buried in the soil. As can be seen from Figure 1, thermoconductivity and heat capacity decrease rapidly as the soil moisture decreases. The result was that very little heat was transferred when the soil dried out.

More recently, research has been done at Cornell University using soil storage in connection with solar greenhouse heating (8,9). Their experiment used six 18-inch diameter steel conduits buried six feet on center under a forty foot long greenhouse. Once again, the major problem was lack of sufficient heat transfer due to drying of the soil around the conduits.

Other than the drying problem, soil appears to be a promising long term storage medium for solar energy utilization. Soil has sufficient heat capacity and thermoconductivity provided adequate water is present. Soil is also readily available and utilization of soil located beneath buildings or feed lots would not require additional space. Any heat losses from a storage system under a building would not be lost, but rather "recaptured" in the building.

A possible solution to the pipe drying problem in the soil is presently being investigated at Purdue (10,11). The proposed system would prevent any moisture migration away from the heat transfer surface by encasing the storage soil mass within an impermeable membrane such as a commercially available pond liner. The soil would be saturated with water, providing good contact with the heat transfer pipes. The pipes, unperforated four inch plastic drainage tile, will be placed in an array within the soil mass, as shown in Figure 2.

A finite-difference heat transfer model for the soil storage has been developed to determine the important parameters and necessary dimensions for adequate thermal storage in soil. The modified Saul'yev iterative procedure was utilized to give a numerical solution to the differential equations governing unsteady-state heat transfer. The program calculates the heat transferred by convection from the air in one pipe to the surrounding soil. The soil mass is assumed to have insulated boundaries. Heat flow in the axial direction is ignored but the length of the pipe is divided into segments and an iterative energy balance is used to calculate the air temperature in the pipe as a function of length.

The computer model was used to determine the most economical pipe spacing for a long term soil storage system. Three different design assumptions were used to evaluate the most suitable spacing: a constant size storage mass, a constant number of heat transfer pipes, and all spacings of the pipe giving an equivalent heat output. The storage was considered to be fully charged at 150°F at the start of the test and the inlet air assigned a constant value of 70°F.

A 120 hour discharging time was chosen to represent a suitable time of operation for use with grain drying. The other physical parameters selected for the computer runs were:

Air density = 0.0667 lbm/ft^3

Air viscosity = 0.045 lbm/ft-hr

Air thermoconductivity = 0.0157 Btu/ft-hr-°F

Air heat capacity = 0.24 Btu/lbm-°F

Soil thermoconductivity = .80 Btu/ft-hr-°F

Soil heat capacity = 36.8 Btu/ft^3-°F

Soil density = 100 lbm/ft^3

Soil bed length = 50 ft

Soil bed diameter = varied from 12 inches to 96 inches

Tile diameter = 4 inches

Air flow rate = 100 CFM/tile

With the assumption that the volume of storage material is the same for all pipe spacing, the encasing liner and escavation costs become constant for all pipe spacings. The only cost which can vary is the cost of the tile. The result of varying the pipe spacing is tabulated in Table 1 and graphically represented in Figure 3. Even though the total energy output decreases with the increase in spacing, the cost per Btu decreases due to the additional energy per pipe transferred at the larger pipe spacing.

Another method of comparing tile spacings is to allow the size of the storage to change and to have an equal number of pipes for all pipe spacings. In this manner the air flow through each system and the tile costs are both held constant while the excavation and liner costs vary with different spacings. The storage bed configuration varies for each spacing but a width to depth ratio of 2:1 and a constant 50 foot length can be assumed for design uniformity. A maximum practical design depth of 20 feet should also be used.

Table 2 gives a tabulation of the results of the analysis which are shown graphically on figures 4, 5, and 6. The cost per Btu was basically constant for the spacings from 12 inches to 28 inches with a slight minimum at the 28 inch spacing. Some of the variability in cost is due to the change in the designed bed sizes.

Probably the most feasible assumption for comparing the varied pipe spacings is equal Btu output over the discharge time. This assumption allows for the variation in the number of pipes as well as the bed size. The bed configuration was based upon the same criteria described above. Table 3 and Figure 7 give the results of this comparison.

The results indicate that a tile spacing of 28 inches on center is the most economical for a long term storage device. However, changes in the relative cost of the materials used or changes in some of the physical parameters may change the optimum pipe spacing.

ROCK STORAGE

The use of rocks to store heat has worked very well with solar energy systems (20,21,22,18). While rock has a heat capacity that is only about one-fifth that of water it has many characteristics that lend itself to use with air heating systems. In the proper configuration a rock storage system can deliver large amounts of heat with a very low pressure drop through the bed. The fact that the particulate nature of rocks forms its own flow path and requires no additional heat transfer surface is also an advantage, as is their low cost and high availability.

The design characteristics of rock storage has been investigated by many researchers (12,13,15,17,19) and information concerning the proper design of a rock storage system is available. Because of this, an appropriately designed storage system based upon the references was selected and used for an economic comparison between a soil storage system and a rock storage system. Since a 4×10^7 Btu soil storage system was used the rock storage system will need to be comparably sized. A storage system of 40 ft x 20 ft cross-sectional area and 32 ft long was chosen.

A simulation model based upon the energy balance analysis of Mumma (14) was used to assure that appropriate heat output was available from this size storage system. An air flow rate equal to that through the 28 inch spaced soil storage system was used to ensure a close comparison between the systems. Other physical parameters chosen were:

Rock diameter = 2 inches

Rock density = 144 lbm/ft^3

Rock heat capacity = .2 Btu/lbm-°F

Rock void space = .4

The air to rock heat transfer coefficient (h) was calculated from an equation empirically derived by Lőf (16).

The computer results show that a sufficient amount of heat was discharged from the storage over the 120 hour period. In fact, a large percentage of the heat was transferred out after only 60 hours. The excellent heat transfer and quick response are characteristic of rock storage systems.

The containing structure for a rock storage system of this size could be a large insulated concrete structure above ground although it would cost nearly three dollars per square foot to build. A more inexpensive possibility would be to put the rocks in the soil. The soil would supply the structural support needed and a pond liner similar to the one used for soil storage could be used to prevent water from entering.

ECONOMIC COMPARISON

The initial construction costs, excluding labor, for a rock storage system and a soil storage system of equal Btu output (40 million Btu) can be directly compared as below:

	SOIL		ROCK	
	quantity	cost	quantity	cost
Storage	633 tons	$ 0.00	1280 tons	$ 6400.00
Liner	3906 ft^2	820.00	5440 ft^2	1142.00
Excavation	633 tons	633.00	1280 tons	1280.00
Total cost	-	$1453.00	-	$ 7822.00
Cost/1000 Btu	-	3.6¢	-	20¢

CONCLUSIONS

There is a need for the utilization of thermal storage with solar supplemented and natural air grain drying. Thermal storage can increase the confidence of such low temperature drying procedures to satisfactorily replace the existing high temperature drying techniques. Focus should be given to the development of long term storage systems which are low in cost and fit the requirements for grain drying. Particular attention should be given to the use of an encased saturated soil thermal storage system because of the inexpensive materials needed for construction. Research is needed which will give experimental and analytical results of the feasibility of such a system for use with grain drying.

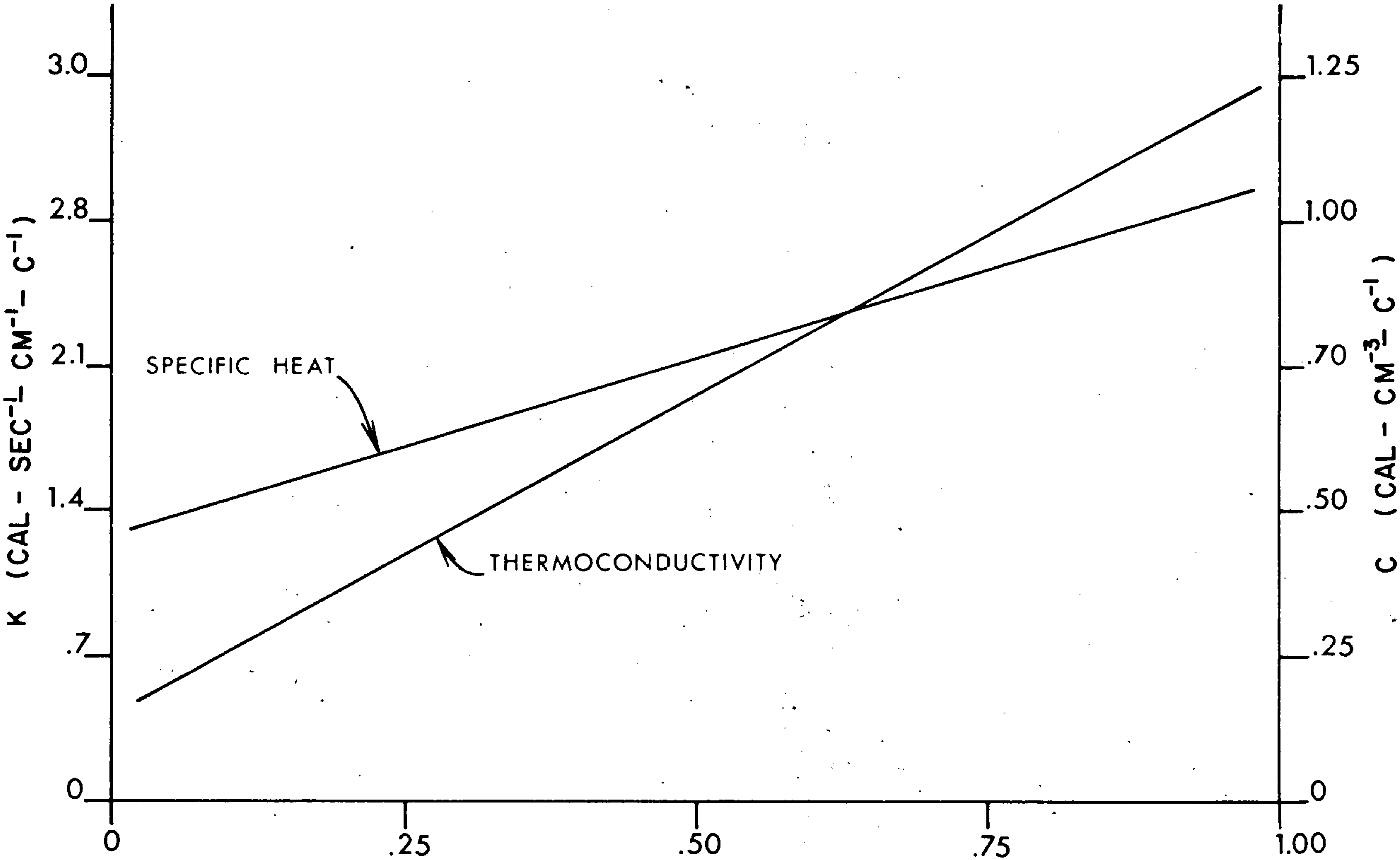
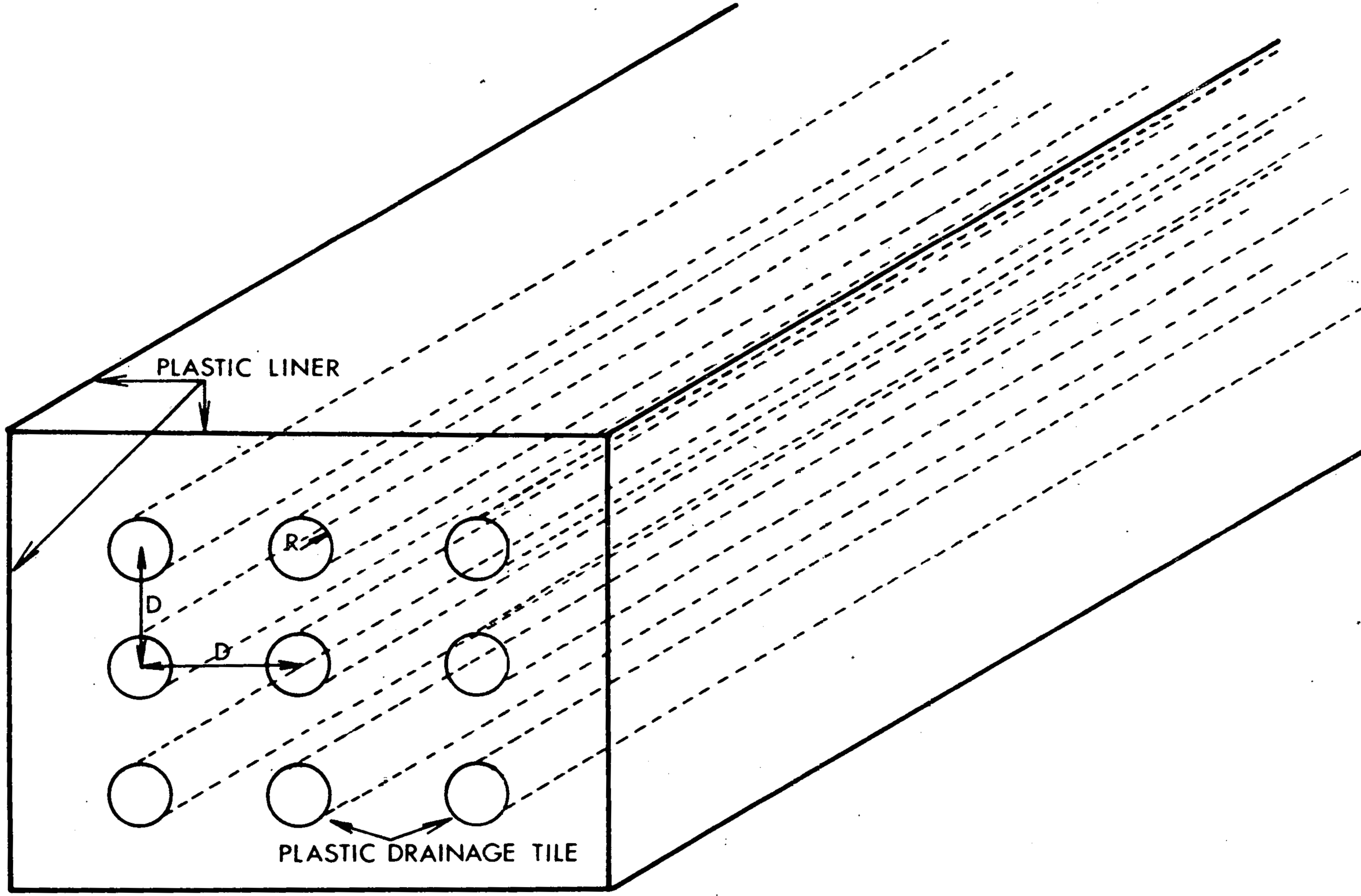

3.0
2.8
2.1
1.4
.7
0
K (CAL - SEC⁻¹ - CM⁻¹ - C⁻¹)
1.25
1.00
.70
.50
.25
0
C (CAL - CM⁻³ - C⁻¹)
SPECIFIC HEAT
THERMOCONDUCTIVITY
0
.25
.50
.75
1.00
VOL. FRACTION OF WATER
VOL. FRACTION OF AIR IN DRY SOIL

FIGURE 1



SOIL STORAGE

FIGURE 2

TABLE 1

EQUAL STORAGE VOLUME - 50 ft. x 20 ft. x 10 ft.

Spacing	No. of Pipes	Pipe Cost @ $.15/ft	120 hrs. Total BTUs Out	120 hrs. $/BTU*	80 hrs. Total BTUs Out	80 hrs. $/BTU	40 hrs. Total BTUs Out	40 hrs. $/BTU
12	800	$ 6,000	51,239,200	1.17×10^{-4}	51,230,400	1.17×10^{-4}	50,452,800	1.19×10^{-4}
16	450	3,375	43,182,000	7.82×10^{-5}	42,951,150	7.86×10^{-5}	39,914,550	8.46×10^{-5}
20	288	2,160	37,546,560	5.75×10^{-5}	36,630,720	5.90×10^{-5}	31,069,440	6.95×10^{-5}
24	200	1,500	33,072,000	4.52×10^{-5}	31,276,000	4.80×10^{-5}	24,204,000	6.20×10^{-5}
28	153	1,147.5	34,420,410	3.33×10^{-5}	30,485,250	3.76×10^{-5}	21,233,340	5.40×10^{-5}
36	91	682.5	25,305,280	2.80×10^{-5}	20,910,890	3.26×10^{-5}	13,445,250	5.08×10^{-5}
48	50	375	16,326,500	2.30×10^{-5}	12,728,500	2.95×10^{-5}	7,693,620	4.87×10^{-5}
60	32	240	11,298,240	2.12×10^{-5}	8,531,200	2.81×10^{-5}	5,008,960	4.79×10^{-5}
72	22	165	8,094,460	2.04×10^{-5}	6,005,780	2.75×10^{-5}	3,469,180	4.76×10^{-5}
96	13	97.5	4,968,080	1.96×10^{-5}	3,620,630	2.69×10^{-5}	2,058,160	4.74×10^{-5}

* $/BTU is figured only upon the variable tile cost.

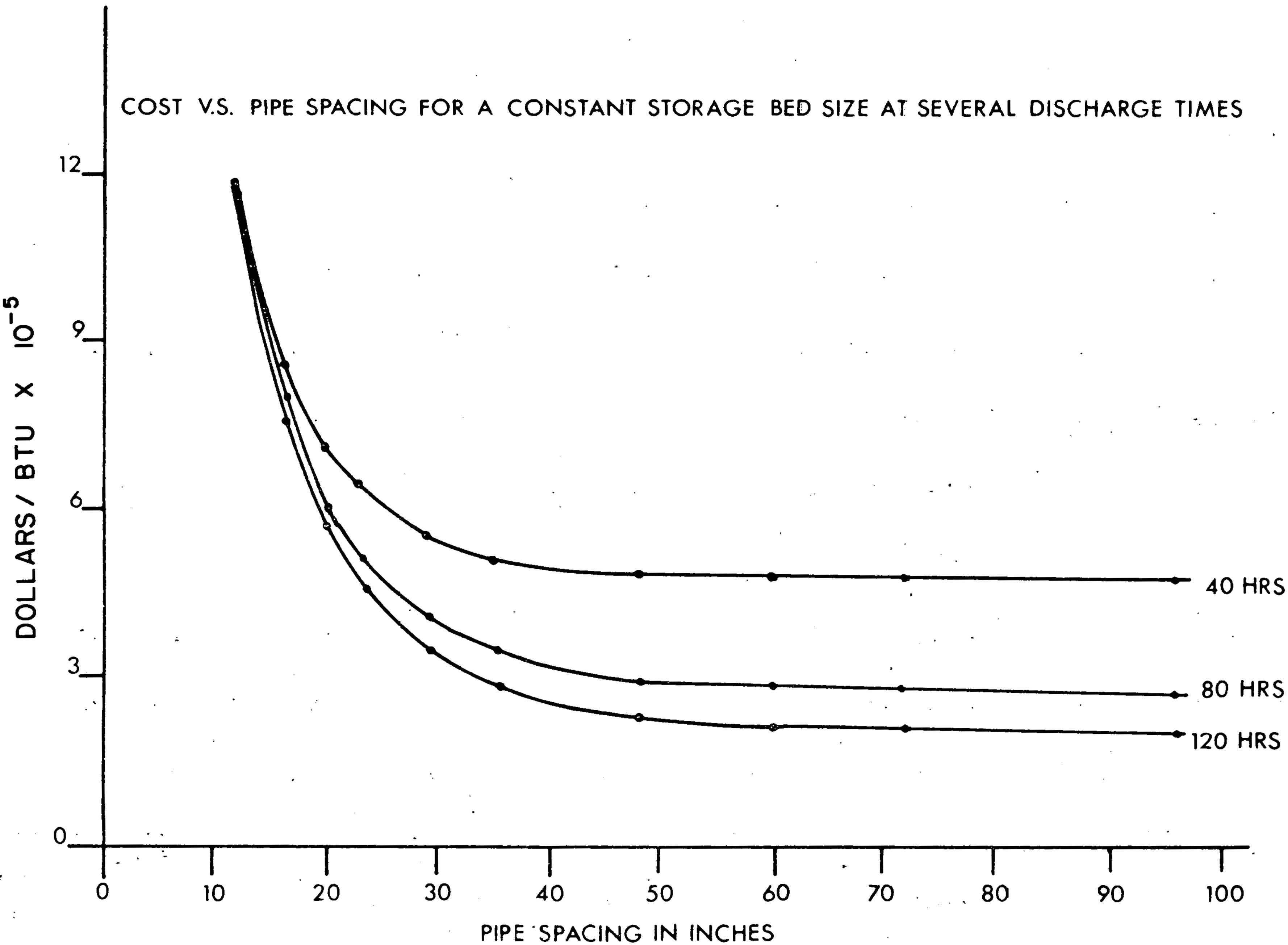

COST V.S. PIPE SPACING FOR A CONSTANT STORAGE BED SIZE AT SEVERAL DISCHARGE TIMES
DOLLARS / BTU X 10^-5
12
9
6
3
0
0
10
20
30
40
50
60
70
80
90
100
PIPE SPACING IN INCHES
40 HRS
80 HRS
120 HRS

FIGURE 3

TABLE 2

EQUAL NUMBER OF PIPES - 200 PIPES

Pipe Spacing (inches)	Bed Size	Volume (ft^3)	Excavation Cost @ $1.00/ton	Surface Area (ft^2)	Liner Cost @ $.21/$ft^2$	Total Btu Output	Total Cost	$/BTU
12	10 X 5 X 50	2,500	$ 125	1,600	$ 336	12,809,800	$ 461	3.60×10^{-5}
16	13.5 X 6.8 X 50	4,590	230	2,207	464	19,192,000	694	3.62×10^{-5}
20	16.7 X 8.37 X 50	6,989	349	2,777	583	26,974,000	932	3.58×10^{-5}
24	20 X 10 X 50	10,000	500	3,400	714	33,072,000	1,214	3.67×10^{-5}
28	23.3 X 11.7 X 50	13,631	682	4,045	849	44,994,000	1,531	3.40×10^{-5}
36	30 X 15 X 50	22,500	1,125	5,400	1,134	55,616,000	2,259	4.06×10^{-5}
48	40 X 20 X 50	40,000	2,000	7,600	1,596	65,306,000	3,596	5.51×10^{-5}
60	62.5 X 20 X 50	62,500	3,125	10,750	2,250	70,614,000	5,383	7.62×10^{-5}
72	86 X 21 X 50	90,300	4,515	14,312	3,006	73,586,000	7,521	1.02×10^{-4}
96	140 X 17.5 X 50	122,500	6,125	20,650	4,337	76,432,000	10,462	1.37×10^{-4}

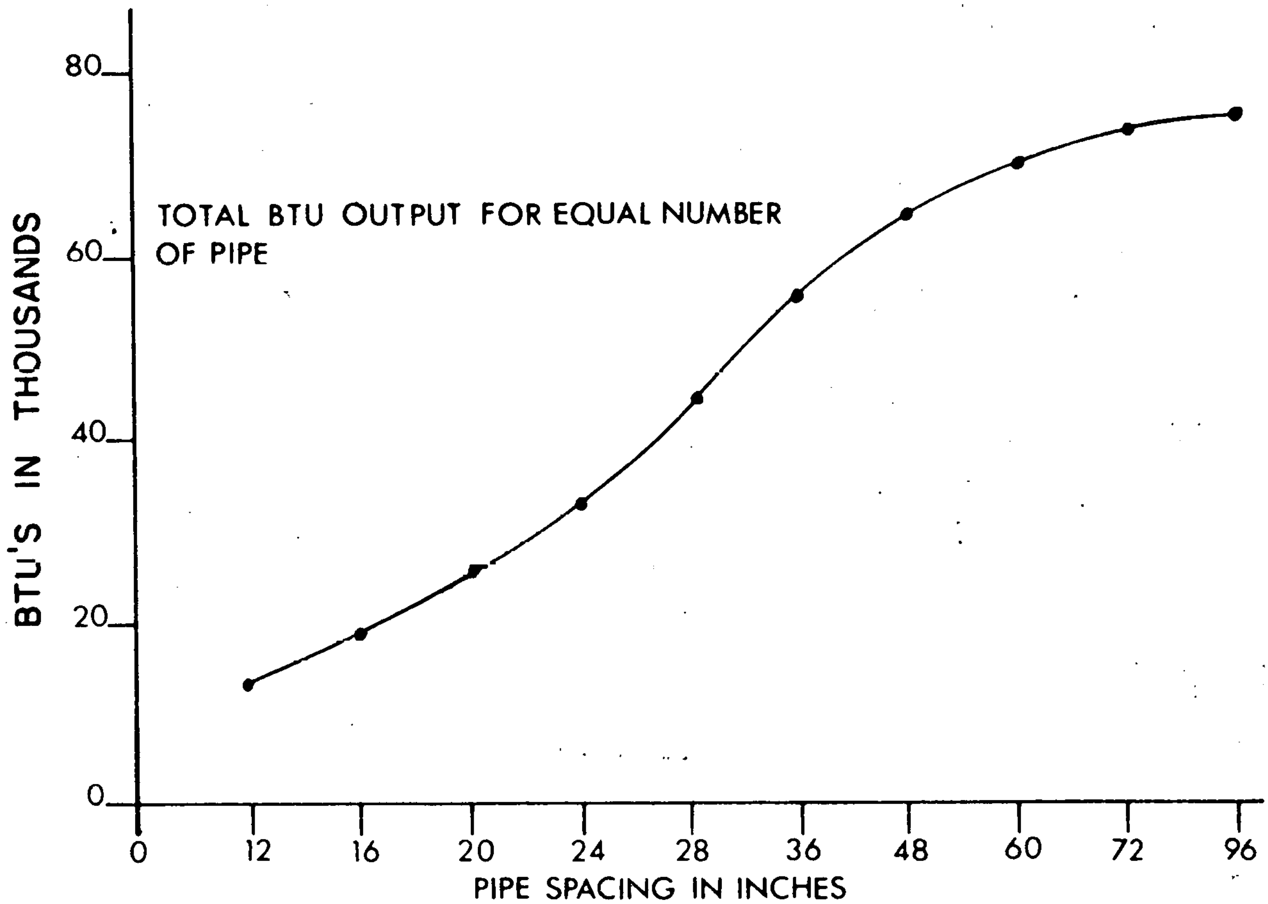


FIGURE 4

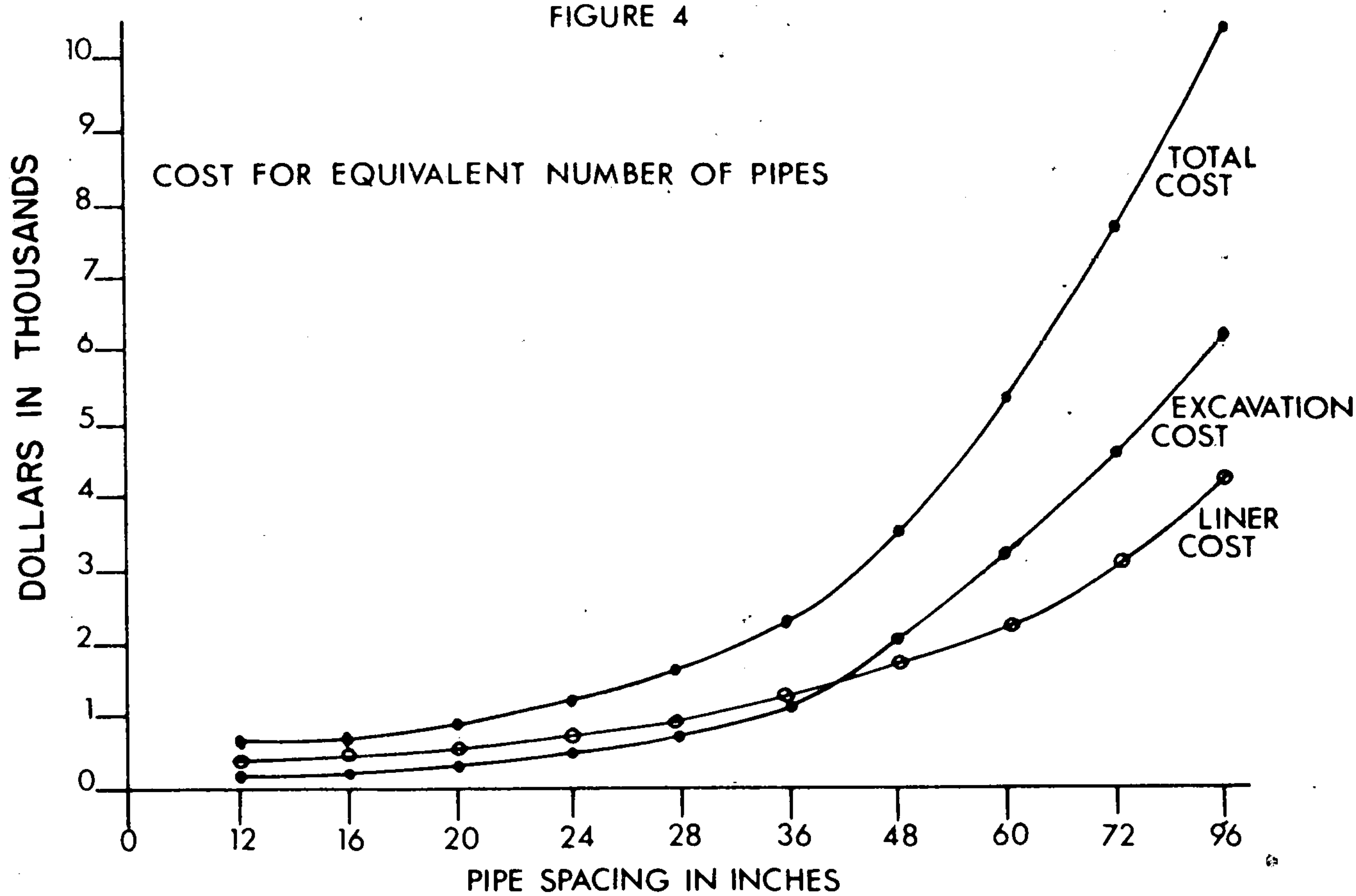


FIGURE 5

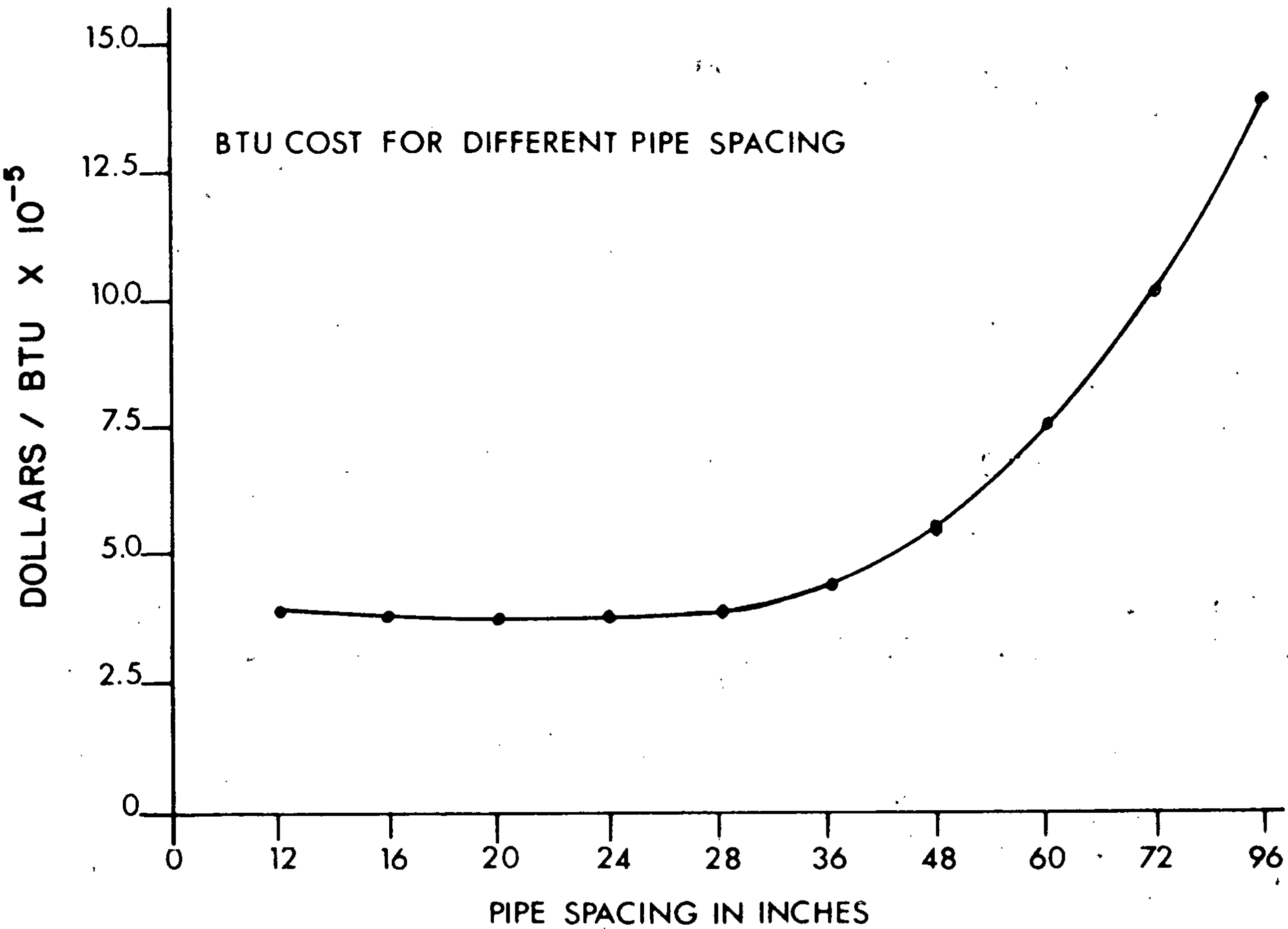

BTU COST FOR DIFFERENT PIPE SPACING
DOLLARS / BTU X 10^{-5}
15.0
12.5
10.0
7.5
5.0
2.5
0
0
12
16
20
24
28
36
48
60
72
96
PIPE SPACING IN INCHES

FIGURE 6

TABLE 3

EQUAL BTU OUTPUT - 4×10^7 BTU'S

Pipe Spacing (inches)	BTU/Pipe	No. of Pipes	Pipe Cost @ $.15/ft	Bed Size	Volume (ft^3)	Excavation Cost @ $1.00/ton	Surface Area(ft^2)	Liner Cost $.21/$ft^2$	Total Cost	$/BTU
12	6.4×10^4	625	$ 4,687	17.5 X 9 X 50	7,875	$ 394	2965	$ 623	$ 5,704	1.43×10^{-4}
16	9.6×10^4	417	3,127	20 X 12 X 50	12,000	600	3680	773	4,500	1.13×10^{-4}
20	1.3×10^5	308	2,310	21 X 10 X 50	10,500	525	3520	739	3,574	8.94×10^{-5}
24	1.7×10^5	243	1,822	20 X 12 X 50	12,000	600	3680	773	3,195	7.99×10^{-5}
28	1.3×10^5	178	1,335	23 X 11 X 50	12,650	633	3906	820	2,788	6.97×10^{-5}
36	2.8×10^5	144	1,080	22.5 X 15 X 50	16,875	844	4425	929	2,853	7.13×10^{-5}
48	3.3×10^5	123	922	28 X 18 X 50	25,200	1,260	5608	1,178	3,360	8.40×10^{-5}
60	3.5×10^5	113	847	35 X 20 X 50	35,000	1,750	6900	1,449	4,046	1.01×10^{-4}
72	3.7×10^5	109	817	45 X 22 X 50	49,500	2,475	8680	1,823	5,115	1.28×10^{-4}
96	3.8×10^5	105	787	84 X 20 X 50	84,000	4,200	13,760	2,890	7,877	1.97×10^{-4}

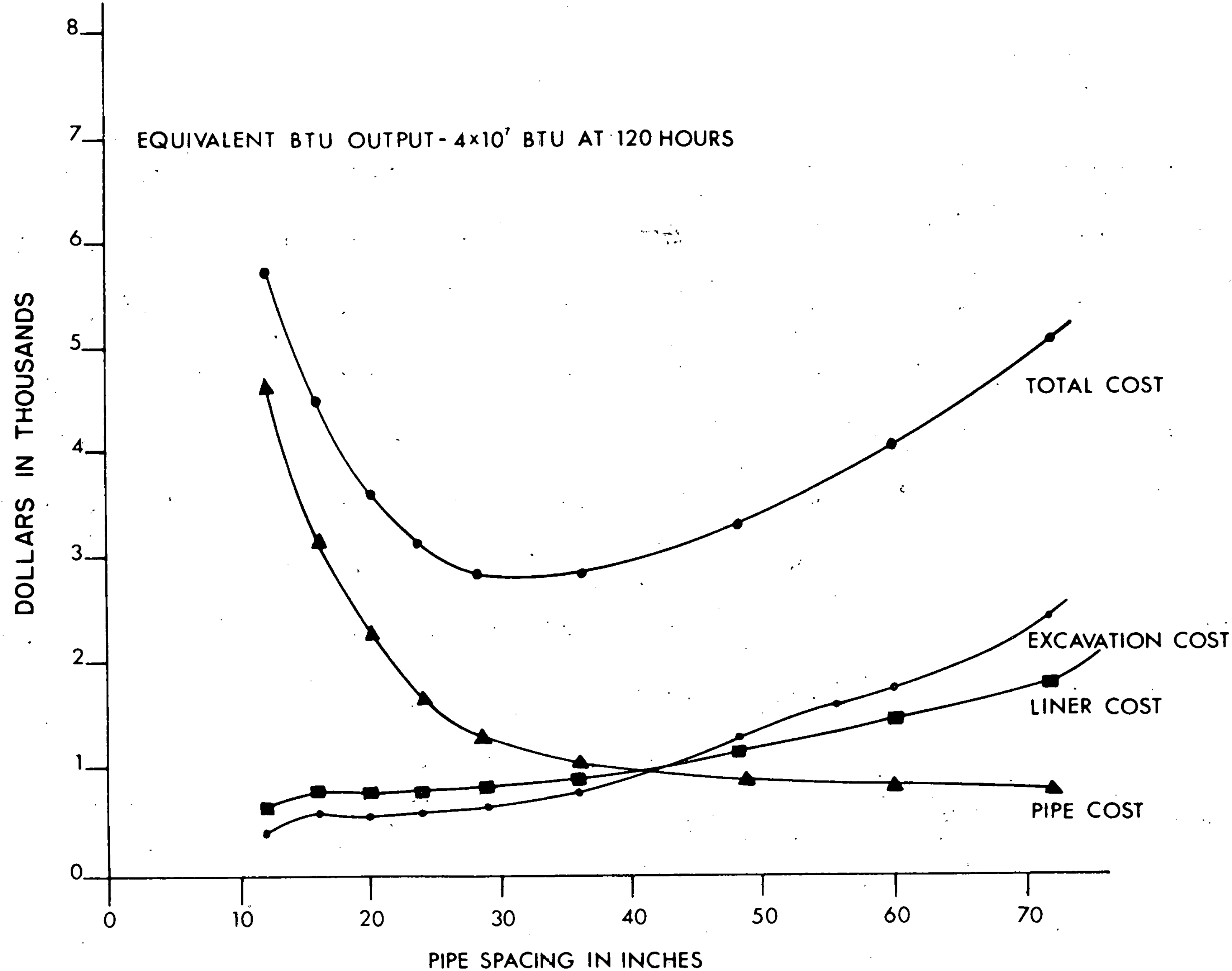

EQUIVALENT BTU OUTPUT - 4×10⁷ BTU AT 120 HOURS
DOLLARS IN THOUSANDS
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
TOTAL COST
EXCAVATION COST
LINER COST
PIPE COST
PIPE SPACING IN INCHES

FIGURE 7

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HEAT STORAGE IN PHASE CHANGE MATERIALS FOR SOLAR GRAIN DRYING

Calvin D. MacCracken[1]

The idea, scientific basis and experimental testing of certain phase change materials (PCM's) for use in solar heat storage was pioneered by Dr. Maria Telkes over the past thirty years and has been extensively reported by her in the literature.[1-12] It has not been until fairly recently, however, that all of the known problems have been overcome, that a house installation has operated successfully for several years, and that engineered production designs have been developed which have low cost and are adaptable to multiple uses in the marketplace.

The two PCM's most practical for and adaptable to solar use and capable of cutting the total volume required compared to rocks or water by a factor of 5 or more are sodium sulfate decahydrate (90°F) and sodium thiosulfate pentahydrate (118°F). Both of them without proper additives will subcool and stratify with solids settling to the bottom causing chemical change.

While a nucleating agent eliminating subcooling had been found for PCM-90,[4,5,10] none has been found for PCM-118. Also both of them were subject to stratification (settling out) which reduced performance. PCM-118 would not be harmed by stratification so long as the vertical dimension of the salt reservoir was not over 1 1/4".

In October 1976 patent 3,986,969 was issued to Dr. Telkes disclosing a practical method of mixing a thixotropic agent, attapulgite clay, to form a gel which prevents settling out in both salts. Shortly another patent will issue to her, both assigned to the University of Delaware, disclosing a nucleating device for PCM-118 which holds salt in crystal form 25°F or more above the melting point. This device has been used in the Solar One house at the University of Delaware and has operated reliably during many cycles since 1973.

The third low cost salt, trisodium phosphate dodecahydrate with additives (150°F), was developed by the writer in 1957 to provide constant temperature shipping containers for certain sensitive mechanisms such as the guidance system on the Polaris missile. This business, originally tradenamed Transit-Heat, passed through several hands but is still manufactured under the name Trans-Temp and has been technically fully reliable.

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[1]President of Calmac Manufacturing Corporation, Box 710, Englewood, New Jersey

My company, Calmac Manufacturing Corporation developed and patented[13] a freezing mat for an ice skating rink, known as ICEMAT , in which a bundle of 64 small flexible plastic tubes are spaced in a 4 ft. wide mat with pairs of tubes co-extruded. By temperature averaging between the two tubes of the pair, since they are connected at one end with a U-bend, a constant heat transfer can take place over the entire rink even though the in and out temperatures may vary by 12°F.

This same principle has been found to be of advantage both in the construction of a mat-type solar collector and in heat exchange to PCM's. A brine flow ice rink and a solar collector have similar heat exchange rates, around 1 Btu per hour per square inch. Considering that ice rinks have mostly gone plastic, there is little justification for the use of copper or aluminum absorber plates in solar collectors since the lower conductivity can be more than made up for by increasing the area (putting the tubes closer together). The SUNMAT solar collector, using EDPM rubber elastomer good to 400°F, carries a high efficiency and yet cuts the cost per square foot by a factor of 4.

By rolling up an ICEMAT grid with a spacer material into a spiral and putting it into a cylindrical open-top plastic tank and filling the tank with PCM, a uniform heat exchange is created throughout the entire mass of the PCM so that all parts of it freeze and melt at the same time. See Fig. 1. Thus expansion and contraction forces due to volume change during fusion are avoided even when ice is frozen. Stainless steel U-bends and clamps are used along with plastic headers. It is important that no more than one type of metal be in contact with the salt and that should be stainless to prevent corrosion from dissimilar metals.

This device is designed for liquid to be used as the heat transfer fluid rather than air. The low temperatures associated with solar work require large air volumes and ducts. Unless the structure is carefully designed to allow very short ducts, the bulky size of the air passages will eat up the space savings of the PCM's.

In solar grain drying it is felt that there is only a limited market for a solar grain dryer by itself because it is used for such a small part of a year. However, a machine shed, for which like closets in a house there is always a need, equipped with a solar collecting roof and south wall, could provide water heating, shop heating, grain drying, fodder drying, livestock heating, and even house heating. This is only practical with a liquid system. Buried insulated plastic tubing and an air coil before the grain dryer fan would allow a blending of outside air and heated air in any proportion.

Thermal storage at 89 or 90°F would be suitable for all these applications provided radiant floor heating is used. Again the tubing mat, with wooden lath filler strips between the tubes and covered with linoleum, tile, carpet or even concrete, makes a very comfortable heating system with only 85°F liquid.

For grain drying it might be most practical to supply solar heat from storage only when the sun is not out and use ambient air alone on sunny days.

For applications requiring storage temperatures under 89° a series of other salts giving eutectic mixtures may be added to the sodium sulfate to lower the melting point. These include potassium nitrate, sodium chloride and ammonium chloride as described in the patent on the thixotropic agent above. Melting points down to 40°F may be achieved.

The cost of the Sunmat collector grid including headers and fittings runs around $1.50 per square foot. It should be mounted on top of the roof running lengthwise so as to use as few headers and U-bends as possible. Other materials purchased locally may run to another $1.00 or so. Heat-Bank storage units run from $1.00 to $2.50 per 1,000 Btu's depending on the size of the installation. Radiant floor mats may run $.75 per square foot not including covering.

By using the sun all year long the investment becomes very practical with paybacks of five years or so. When financed by long term mortgages and with various tax credits applicable, it can make you money from the start, save national energy, give you protection against shortages, dry your grain on time, and give you a new building in the bargain.

FIG. 1

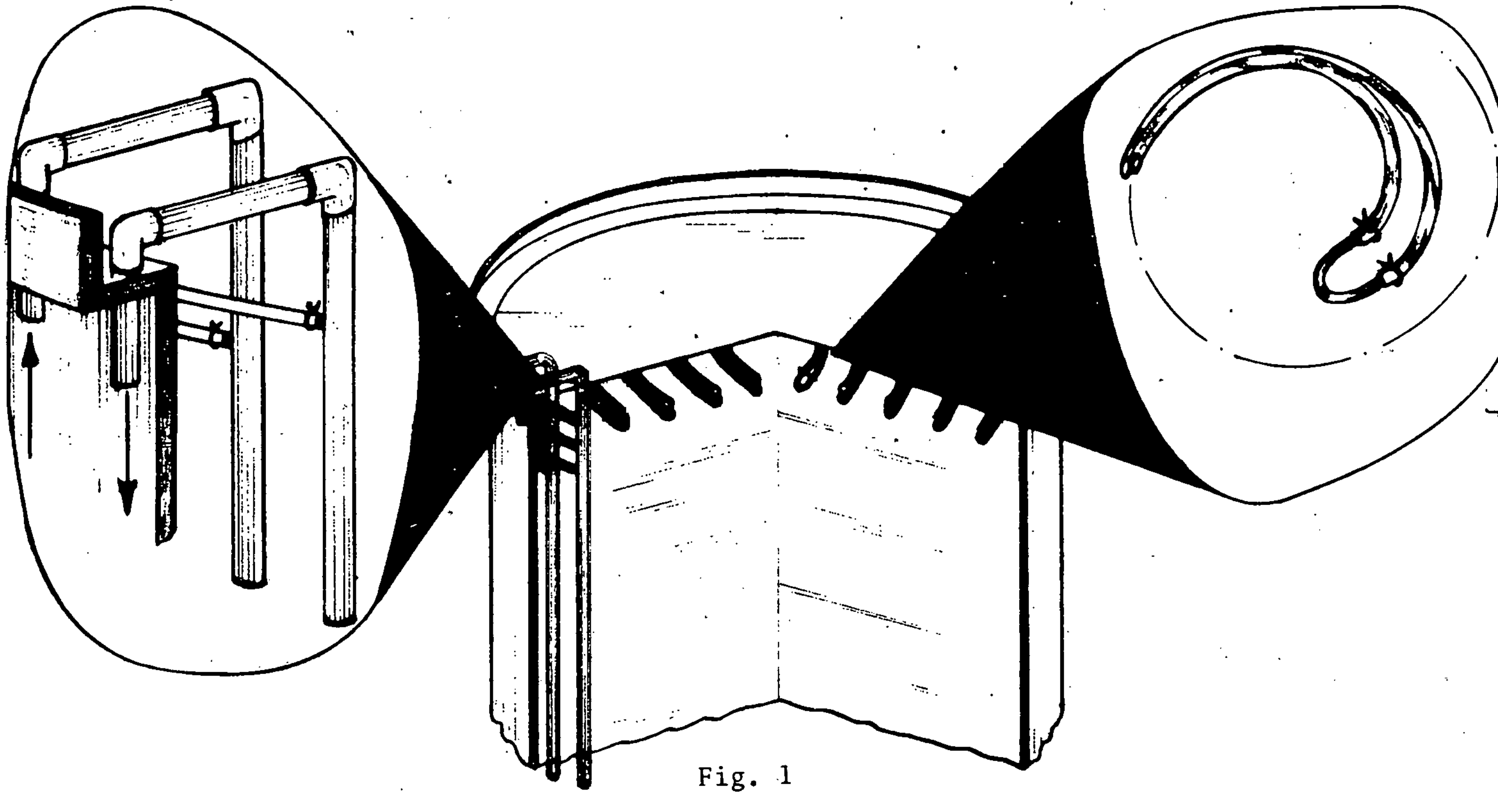

Fig. 1

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SOLAR DRYING OF WHEAT

John R. Barrett, Jr.[1] and Jay B. Stevens[2]

INTRODUCTION

Harvest of high-moisture wheat followed by low-temperature in-bin drying can potentially benefit a grower who needs to 1) improve the quality of grain and reduce harvest losses, 2) harvest between rains in inclement weather, 3) better utilize equipment and labor over a longer harvest period, and/or 4) plant a second soybean crop up to 7 days earlier than would be possible without in-bin drying.

Although some Midwest farmers routinely artificially dry wheat rather than letting it dry naturally in their fields, drying is not a normal practice in the Midwest, as it is in some parts of Canada and the USSR where excessive moisture at harvest is a major problem.

RESEARCH

During the summers of 1975 and 1976, research was conducted by ARS, USDA, and Purdue University to compare in-bin drying of wheat using solar heated air with drying using unheated air. Investigations were jointly sponsored by ERDA, ARS-USDA, and the Purdue Agricultural Experiment Station through the Departments of Agricultural Engineering and Agronomy.

Wheat was combined by cooperating farmers in late June 1976 to fill two 18-foot diameter bins with approximately 1700 bu. of 21-23% grain each. Depth was limited to about 7 feet, which is less than for drying of corn. This reduction is caused by the greater resistance of wheat to air flow. The fans supplied 2-2.5 cfm air flow per bushel.

One bin was dried with solar heated air from 2 horizontal suspended-plate inflated plastic (pvc) collectors and the other with unheated air. The maximum increase of temperature of heated air was 29°F. Field dry-down, grain quality, and harvest, environmental, and in-bin drying conditions were monitored.

OBSERVATIONS, RESULTS, AND DISCUSSION

Prior research has shown that input drying air temperatures should be held below 140°F to avoid damage to milling quality, and below 110° (better yet 100°F) for seed wheat, and that at least 2 cfm air flow per bushel is required on a continuous basis. The following are observations, results, and discussion of our research on in-bin wheat drying.

1. Using present-day combines, wheat can be harvested with up to 24% moisture content. In the 20-24% range heat is needed initially to eliminate the high potential for spoilage at summer temperatures when

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1 Agricultural Engineer, ARS, USDA, and Assistant Professor, Department of Agricultural Engineering, Purdue University, West Lafayette, IN 47907

2 Graduate Instructor, Department of Agricultural Engineering, Purdue University, West Lafayette, IN 47907

grain mass temperatures are 85-95°F.

2. There are only 7-10 days to reduce the moisture content of the grain above the drying front to less than 18%. It is questionable that this can be reliably accomplished year after year with unheated air.
3. Past recommendations that drying with unheated air is adequate are based on the assumption that initial moisture content is no higher than 19%.
4. The usual methods for moisture determinations are not reliable in the 20-30% range. Also, few of us are experienced in determining by observation the moisture content of wheat above the 18-20% range.
5. Solar heating of air for low-temperature in-bin wheat drying is adequate and acceptable for wheat harvested with up to 24% moisture if grain depths in the bins are limited to allow fans to maintain at least 2 cfm air flow per bushel. Fans should be run continuously to cool the grain during evening hours.
6. When unheated air drying is done, i.e. starting with grain of less than 19% moisture, fans should be run continuously until the grain is down to 14.5 to 15%. At this point, the nighttime rewetting can easily offset drying done during the day. Additional drying may be accomplished by operating the fan only during the daytime until the upper layer of grain is at the desired 13 to 13.5% range. Soon afterwards, the fan should be operated 1 or 2 dry nights to cool the grain heated by the warm daytime temperatures.
7. Wheat quality and tests weights can be increased frequently from #2 to #1 grade, and harvest losses significantly reduced with early, high-moisture harvest and low temperature drying.
8. Better management of labor, equipment, and facilities can be a benefit of wheat drying.
9. In-bin drying can make possible up to 7 days earlier second-crop planting of soybeans at a time when soil moisture conditions are critical for germination of soybean seed. Earlier planting can increase yield 1/2 bushel per acre per day.
10. Mold and fungi presence and development determinations made from field and bin samples showed that no problems developed with the solar dried wheat; none of the traditional toxin producing organisms were found. Some mold growth, including penicillium, occurred in the upper levels of the wheat dried with unheated air.
11. Solar drying of wheat should only be considered if facilities and solar collectors are already available for corn drying, space heating or farmstead systems heating.

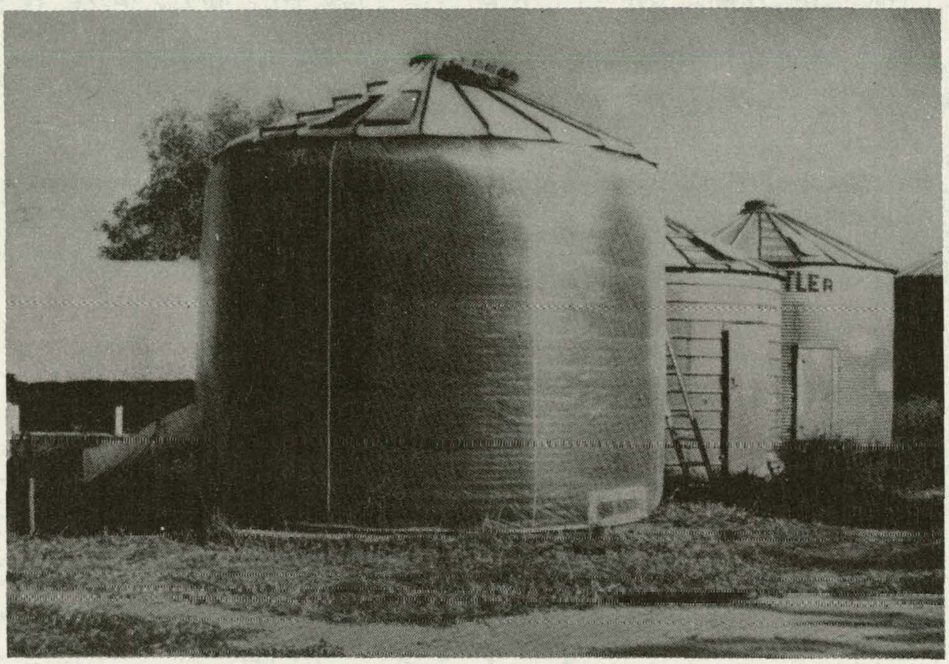
RESEARCH IN PROGRESS

The potential benefits of utilizing solar energy to dry wheat are continuing to be evaluated. Technology is being developed to assist with decision-making based on how wheat harvest, drying, and weather interact to influence the production efficiency and potential for success of double-cropping of wheat and soybeans. A weather based wheat drying simulation model is being developed and validated.

EXPERIENCE WITH A "BIN-BIB"SOLAR COLLECTOR

Ralph Lipper[1] and J. C. Welker[2]

In the fall of 1976, we tried a different kind of bin-wall solar collector that, with modification,might be of interest to those wishing to combine the use of solar energy with natural air or low temperature grain drying. It was an enclosed envelope or "pillow" with its front side made from nylon reinforced clear plastic film and its back side from black film. That envelope was strapped around the south two-thirds of a 14-foot diameter steel bin. Five nylon straps, like aprong strings, went the rest of the way around the bin and were tied to secure the "bin-bib" in place. The fan discharged into the space between the two films. An opening in the black plastic was aligned with the bin wall opening that led to the under-floor plenum.



[1]Ralph Lipper, Professor of Agricultural Engineering, Kansas State University, Manhattan, Kansas.

[2]J. C. Welker, Research Assistant, Agricultural Engineering Department, Kansas State University, Manhattan, Kansas.

One thousand bushels of sorghum grain loaded at 25.8 percent moisture (w.b.) between September 24 and 28 were dried with 1.7 cfm per bushel. Average moisture content reached 15.8 with the surface at 16.6 percent on November 8. The plan included a check bin using natural air, but the grain moisture was down to 17.3 percent by the time filling was completed after harvest delays on October 2.

We encountered two problems. Rats chewed holes in the plastic to maintain their accustomed access to the under-floor plenum. Hoop stresses caused pulling of the clear plastic at sewed seams with the collector under pressure. We later sewed nylon straps to the collector to form air channels and divide up the area over which air pressure acted to produce the stresses. Another solution might be to adapt to a two-fan system as has been done with other collector configurations.

This collector could be laid on a roof, on the ground, or strapped to a convenient building wall if any of those alternatives presented a better surface to the sun than a round bin wall. Time to mount the collector on this bin wall was one hour per man. Thermo-Flex, Inc. of Salina, Kansas, estimated that they could sell collectors like this one for $1.00 per square foot of area covered.

FEASIBILITY STUDY OF IN-BIN CORN DRYING
IN MISSOURI
USING SOLAR ENERGY

F. W. Bakker-Arkema[1], D. B. Brooker[2], and M. G. Roth[3]

ABSTRACT

The feasibility of in-bin corn drying using solar energy was investigated by conducting an in-depth simulation study in Missouri. The main conclusions are that in Missouri:

1. Solar drying and low temperature (natural air) drying are equally feasible at the same airflow and initial moisture content values.
2. Solar drying reduces the hours of fan operation. However, the KWH or BTU savings are minimal.
3. Energy savings from solar corn drying are not sufficient to justify the use of solar collectors.

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[1]F. W. Bakker-Arkema, Professor of Agricultural Engineering, Michigan State University, East Lansing, Michigan

[2]D. B. Brooker, Professor of Agricultural Engineering, University of Missouri, Columbia, Missouri

[3]M. G. Roth, Department of Computer Science, University of Illinois, Urbana Illinois

List of Symbols

C	specific heat, BTU/lb-F
f	thin layer function, lb/ft^3-hr
g	airflow rate, lb/hr-ft^2
h	convective heat transfer coefficient, BTU/hr ft^2 F
H	absolute humidity, lb/lb
h_{fg}	latent heat of vaporization, BTU/lb
M	moisture content, dry basis (decimal)
t	time, hr
T	temperature and air temperature, F
x	depth, ft
ρ	dry weight product density, lb/ft^3
θ	product temperature, F

Subscripts

a	air
p	product
v	water vapor
w	liquid water

I. Introduction

A considerable amount of energy is required for the artificial drying of cereal grains. In the midwestern states of the U.S. the energy is usually supplied by the fossil fuels propane and natural gas. Due to the ever decreasing availability of these products, new energy sources or different drying methods are needed for drying grains. Solar energy may become the new source, natural/low temperature drying the new method. The diffuse nature of solar energy precludes the use of high temperature dryers. A low temperature deep bin drying system seems most likely to be technically and economically feasible.

The general objective of this study was to assess the feasibility of in-bin solar corn drying in the state of Missouri. A computer simulation model was developed for predicting the drying behavior of the grain under different drying conditions. Specific objectives of the project included:

1. Development and testing of a solar in-bin drying model.
2. Evaluation of the effect on in-bin solar drying of (a) starting date, (b) collector size, (c) collector efficiency, (d) airflow, (e) initial moisture content, and (f) grain depth.
3. Comparison of natural air and solar heated air drying.

II. In-Bin Solar Drying Simulation

2.1 Introduction

Most applications of solar energy to grain drying utilize low airflow rates applied for a period of a month or more. This approach is adopted because of the relatively limited amount of energy that is available from a solar collector during the fall months of the year. The MSU Fixed Bed Dryer Model (Bakker-Arkema et al., 1974) is unsuitable for such applications because the execution time of the computer program increases drastically as the inlet airflow is reduced. To simulate 30 days of storage at an airflow of 1 cfm/bu would require approximately 30 hours of computer time using this model.

The new model described here accomplishes the same simulation in approximately 3 minutes and requires less computer memory. A comparison of the two models showed agreement to three decimal places for most variables. To achieve the increased execution speed the basic fixed bed equations were modified and a new solution technique was employed to solve the equations.

2.2 Mathematical Model

The basic equations describing heat and mass transfer in a in-bin fixed bed dryer are (Brooker at al., 1974):

$$g_a \frac{\partial}{\partial x} [C_a T + HC_v(T - 212) + Hh_{fg}] = ha(T - \theta) \quad (2.1)$$

$$\rho_p \frac{\partial}{\partial t} [C_p \quad + MC_w(\theta - 212)] = ha(T - \theta) \quad (2.2)$$

$$g_a \frac{\partial H}{\partial x} = -r_m(T,H,M,t) \quad (2.3)$$

$$\rho_p \frac{\partial M}{\partial t} = r_m(T,H,M,t) \quad (2.4)$$

A first-order explicit finite difference solution of these equations requires that Δx be varied proportionately to airflow, g_a, to assure stability. At low airflows Δx must be small and the execution time of the program increases correspondingly. The physical interpretation of this behavior is that as g_a decreases, the air and grain temperatures become nearly equal.

The difference between the air and grain temperatures provides the driving force for the convective heat transfer, as shown by the terms on the right hand side in eqns. 2.1 and 2.2. The relative error in the temperature difference increases as the magnitude of the difference decreases. To offset the loss in accuracy, each temperature must be computed in double precision at low airflows.

At the low airflow rates used for solar drying, the difference between the air and grain temperatures is unmeasurable. To obtain a more efficient solar drying simulation model, the heat and mass transfer equations are rewritten in terms of a single temperature variable as the air temperature and the grain temperature are assumed to be equal. Then by adding eqns. 2.1 and 2.2 and replacing θ by T the resulting equation is obtained:

$$g_a \frac{\partial}{\partial x} [C_a T + HC_v(T - 212) + Hh_{fg}] + \rho_p \frac{\partial}{\partial t}[C_p T + MC_w(T-212)] = 0 \quad (2.5)$$

By rearranging and collecting terms, eqn. 2.5 can be written in terms of the derivatives of the state variables T, H, and M:

$$g_a \frac{\partial T}{\partial x} (C_a + HC_v) + g_a \frac{\partial H}{\partial x} (h_{fg} + C_v T - 212C_v)$$

$$+ \rho_p \frac{\partial \theta}{\partial t} (C_p + MC_w) + \rho_p \frac{\partial M}{\partial t} C_w(\theta - 212) = 0 \qquad (2.6)$$

Eqn. 2.6 can be simplified by writing $\partial M/\partial t$ in terms of $\partial H/\partial x$. By combining eqns. 2.3 and 2.4 and substituting into eqn. 2.6, the following equations are obtained for in-bin solar drying at low airflows:

$$\rho_p(C_p + MC_w) \frac{\partial T}{\partial t} + g_a(C_a + HC_v)\frac{\partial T}{\partial x} + g_a[(C_w - C_v)(212 - T) + h_{fg}]\frac{\partial H}{\partial x} = 0 \qquad (2.7)$$

$$\rho_p \frac{\partial M}{\partial t} + g_a \frac{\partial H}{\partial x} = 0 \qquad (2.8)$$

$$\rho_p \frac{\partial M}{\partial t} = r_m(T, H, M, t) \qquad (2.9)$$

2.3 Simulating Condensation

Eqns. 2.7-2.9 contain no provision for simulating condensation and rewetting. Any water in the system must exist in the air humidity, H, or be contained in the grain moisture content, M. To accurately model condensation, equations describing rewetting and redrying are necessary. A new variable, W, can then be added to the system to account for any condensed water on the grain. This approach has been used successfully by Lerew and Bakker-Arkema (1976) to model condensation during reconditioning of potatoes.

The model developed here uses a simplified technique, in which any condensed water is restored to the moisture content of the grain. Lacking a thin-layer equation which can model wetting the redrying, this approach seems to be the best possible.

If the relative humidity exceeds 100% during the solution of the fixed bed equations, H must be adjusted to obtain a feasible relative humidity. Any change in H also affects the mass and energy balances of the system and requires that T and M be re-evaluated. To assure that eqns. 2.7-2.9 are satisfied, the new values of T, H, and M should be computed along a line of constant enthalpy starting with eqn. 2.5.

III. Results

3.1 Output Format

The moisture contents (dry and wet basis, %), the humidities (absolute and relative, decimal), the air-grain temperatures (^oF), the corn equilibrium moisture contents (dry basis, %) and the dry matter losses (%) at the different bin-depths are printed out for a particular drying time. In addition, the ambient air temperature (^oF), the insolation (BTU/ft^2hr), the average dry and wet basis moisture contents (%), the total radiation since the start of drying (BTU), the average dry matter loss (%) and the total amount of water evaporated (lb) are printed.

3.2 Required Weather Data

Averaging the weather data inputs for the in-bin solar grain drying simulation model over a 24-hour period has two advantages: (1) saving of computer time and (2) greater availability of weather data for different locations. In this part of the study the question was posed if the averaging of weather parameters over different periods adequately represents the cyclic behavior of solar radiation. One, six, twelve and twenty-four hour averages of the weather parameters were used as input values for ten years of Missouri weather.

The principle results of the study on averaging weather data input for in-bin solar grain drying simulations are:

1. the absolute errors in the simulation results for moisture content and dry matter loss due to averaging weather data over a 24-hour period are small;
2. the moisture content and dry matter loss are slightly underestimated using averaged weather data because of the nonlinear effects of dry bulb temperature, dew point temperature and solar radiation on the drying process;
3. the use of hourly weather input data or values averaged over a 12-hour period recommended for solar drying simulations.

3.3 Simulation

In order to effectively investigate the effect of solar energy utilization on in-bin drying, an arbitrary standard was selected for each of the drying input conditions. Table 1 lists the conditions chosen. The simulations were continued until the maximum moisture content in the bin reached 15.5% w.b.

The solar drying process was interrupted if by January 1 the minimum temperature in the bin had become less than 28°F; drying was restarted by March 1. In the simulations it was assumed that the fan adds 2°F to the temperature of the air.

Table 2 lists the simulated average moisture content, the average dry matter loss, the dry matter loss at the 12-foot level, the total radiation per square foot of collector and the time required by the top layer in the bin to reach a MC of 15.5%.

The figures in Table 2 illustrate that the in-bin solar dyring system successfully dries the corn eight out of ten years. Thus the probability of success is 0.8. Only in 1949 and 1954 did the corn mold (DM_{12} is larger than 0.5).

3.4 Effect of Starting Date

The starting date of the in-bin solar corn drying process greatly affects the drying results. Table 3 shows that a later start usually improves the chance for success. As drying is postponed, the dry matter losses decrease substantially not withstanding the longer period required for the drying process. The explanation for this phenomenon is that the rate of dry matter decomposition (and thus the molding) is very much influenced by temperature. Since the ambient temperatures are higher earlier in the drying season, the corn will mold more rapidly despite a usually faster drying rate.

3.5 Effect of Collector Size and Efficiency

The effect of collector size and collector efficiency is illustrated in Tables 4 and 5 and in Figures 1, 2 and 3. As is evident from the data presented, the drying rates increase with an increase of collector size and efficiency. There is relatively little difference in the dry matter losses of the corn within the range of collector sizes and efficiencies investigated (Figure 3). However, larger collectors with higher efficiencies result in decreased fan operation.

In evaluating the effect of collector size and efficiency it should be clear that doubling collector size is equivalent to doubling the collector efficiency. This should be kept in mind in evaluating the results presented in tables of this report.

3.6 Effect of Initial Corn Moisture Content

Table 6 indicates that the initial corn moisture content is an important parameter in the possible success of in-bin solar drying. In an average fall the initial moisture content can not be much above 22 percent. In a favorable year corn at 26% can be solar dried. The maximum moisture content of corn to be solar dried in a wet and cloudy fall is about 20-21 percent as long as the airflow rate is in the 2.0-2.5 cfm/bu range.

The limitation of a maximum moisture content of only slightly over 20 percent means that high temperature drying or the use of the higher airflows be required for much of the corn presently harvested in the Midwest. Partial drying at high temperatures could be followed by lower temperature solar or natural air drying.

3.7 Effect of Bin Depth

Table 7 illustrates the effect of bin depth upon the drying behavior of the bin. The data show that as long as the airflow rate and the collector size per unit of volume of grain are constant, the drying behavior is not affected by bin depth. Thus, as long as in the design the airflow rate and the collector size are based on a per bushel basis, results obtained for a 10 foot deep bin are equally valid for a 16 foot deep unit.

3.8 Effect of Airflow

Airflow is a critical parameter in in-bin solar grain drying. Table 8 illustrates this fact for six flow rates. The drying rates at high airflows are higher, the dry matter losses lower than at low airflows.

For Missouri airflow rates for in-bin solar and non-solar (natural air) corn drying systems should be at least 2.0 cfm/bu and preferably 2.5 cfm/bu to insure minimum grain quality deterioration.

3.9 Effect of Solar Energy

Table 9 makes a comparison between solar and non-solar in-bin corn drying for a number of different starting dates of drying in Columbia, Missouri. Figures 4 and 5 depict the dry matter loss for both cases.

A close study of the data in Table 9 indicates that although solar drying decreases the drying time, the dry matter losses (and thus the rate of mold development) are not decreased materially by adding a solar collector to a corn bin. In other words, low temperature drying without the use of solar energy is as effective as solar drying. Non-solar (low temperature) drying requires longer drying times and therefore more electrical energy for operating the drying fan. However, the savings in terms of BTU/bu are small, especially at the later starting dates of drying.

IV. SUMMARY

A non-equilibrium model for simulating in-bin solar grain drying has been presented. The model has been used to predict the drying rates and dry matter losses of shelled corn using weather data for Columbia, Missouri and (to a limited extent) Lansing, Michigan. The effect of weather data averaging, start of drying date, collector size and efficiency, airflow, initial corn moisture content and bed depth on the performance of the in-bin solar drying system was investigated. In addition, the solar in-bin drying system was compared to the equivalent natural air drying system.

The following conclusions should be drawn:

1. The MSU solar in-bin drying model adequately predicts the solar and natural air drying behavior of shelled corn.
2. The use of 24-hour average weather conditions as input parameters to the solar model is acceptable although 1-hour or 12-hour averaged values are recommended.
3. Due to varying weather conditions there is a significant difference from year to year in the drying rate of corn dried in solar in-bin dryers. Therefore the optimum design requirements will be different from year to year.
4. Solar drying has a better chance for success when started later in the fall.
5. The maximum safe initial moisture content for corn in Missouri for a solar in-bin drying system is approximately 21 percent as long as the airflow is not above the 2.0-2.5 cfm/bu range.
6. Airflow rate is the most critical parameter in the successful design of in-bin solar grain drying. The correct value depends on the initial moisture content, the expected weather conditions and the collector design. For Missouri an airflow rate of at least 2.0 cfm/bu (better yet, 2.5 cfm/bu) is recommended with a maximum initial moisture content of about 21%.

7. Larger collectors with higher efficiencies reduce the period of fan operation but not necessarily result in a decrease of dry matter losses (or mold development).
8. If design of an in-bin solar drying system is based on an airflow per bushel and collector size per bushel, the corn depth in the bin is immaterial.
9. In-bin solar drying results in more frequent over-drying of the bottom layers than is the case with natural air drying.
10. The quality of the corn dried in a solar system is similar to that dried with natural air. The energy requirements of a solar drier are reduced due to less fan operation but the energy savings are not sufficient to justify solar collectors.

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Mr. S. Becker, Department of Agricultural Engineering, Michigan State University, East Lansing, Michigan

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Table 1. Standard drying conditions for in-bin solar corn drying simulations.

Initial moisture content	22.0% w.b.
Airflow rate	2.0 cfm/bu
Bin depth	12.0 ft
Collector area	0.7 ft^2/bu
Collector efficiency	40.0%
Starting date	October 1
Weather parameter input	hourly
Location	Columbia, Missouri
Solar constant*	19.9

* The solar constant (SC) is defined by the following relationship (Thompson, 1976)

$$SC = \frac{(\text{collector area, ft}^2)(\text{collector eff, \%})}{(\text{airflow, cfm/bu})(0.703)}$$

Table 2. Comparison of in-bin solar corn drying for different years in Columbia, Missouri. Drying conditions are listed in Table 1.

Year	Rad x 10^5 BTU/ft^2	Time hr	MC_{av} %wb	DM_{av} %	DM_{12} %
1946	1.16	276	12.3	0.08	0.18
1947	1.32	312	12.6	0.14	0.32
1948	1.55	420	13.3	0.10	0.18
1949	1.42	411	12.9	0.29	0.58
1950	1.42	377	14.1	0.16	0.27
1951	1.39	360	12.9	0.20	0.34
1952	1.28	276	11.8	0.05	0.08
1953	1.31	300	12.4	0.09	0.18
1954	1.50	456	12.3	0.27	0.54
1955	1.56	456	12.2	0.19	0.34

NOTE: rad - radiation received during the period of time listed

time - time since start of drying; average bin moisture content has decreased below 15.0% and the moisture content at the top of the bin has decreased to 15.5%.

MC_{av} - average moisture content in the bin

DM_{av} - average dry matter loss in the bin

DM_{12} - dry matter loss at the top of the bin

Table 3. Comparison of in-bin solar corn drying for different starting dates of drying in Columbia, Missouri. Drying conditions (except starting date) are listed in Table 1.

Starting Date	Rad x 10^5 BTU/ft^2	Time hr	MC_{av} %wb	DM_{av} %	DM_{12} %
1949 Sept 1	1.80	449	13.9	0.22	0.43
Sept 15	1.63	341	12.7	0.20	0.34
Oct 15	0.42	647	13.9	0.14	0.24
1951 Sept 1	1.49	388	13.1	0.33	0.64
Sept 15	1.57	324	12.9	0.15	0.30
Oct 15	1.33	574	14.0	0.12	0.20
1952 Sept 1	1.43	270	12.1	0.16	0.36
Sept 15	1.44	287	11.9	0.13	0.24
Oct 15	1.27	287	11.1	0.04	0.07

Table 4. Comparison of in-bin solar corn drying for different collector sizes in Columbia, Missouri. Drying conditions are listed in Table 1.

Collector ft^2/bu	Rad x 10^5 BTU/ft^2	Time hr	MC_{av} %wb	DM_{av} %	DM_{12} %
0.18	0.38 (1949)	712	14.8	0.62	0.89
	0.46 (1951)	504	13.9	0.23	0.39
0.35	0.77 (1949)	588	14.9	0.34	0.61
	0.81 (1951)	432	13.9	0.22	0.37
0.70	1.42 (1949)	411	12.9	0.29	0.58
	1.39 (1951)	360	12.9	0.20	0.34

Table 5. Comparison of in-bin solar corn drying for different collector efficiencies in Columbia, Missouri. Drying conditions are listed in Table 1.

Collector eff %	Rad x 10^5 BTU/ft^2	Time hr	MC_{av} %wb	DM_{av} %	DM_{12} %
0.40	1.42 (1949)	411	12.9	0.29	0.58
	1.39 (1951)	360	12.9	0.20	0.34
0.60	1.21 (1949)	358	12.4	0.27	0.56
	1.22 (1951)	309	12.0	0.20	0.34
0.80	1.02 (1949)	312	11.9	0.25	0.55
	1.00 (1951)	270	12.2	0.20	0.34

Table 6. Comparison of in-bin solar corn drying for different initial moisture contents in Columbia, Missouri. Drying conditions are listed in Table 1.

Initial MC %wb	Rad x 10^5 BTU/ft^2	Time hr	MC_{av} %wb	DM_{av} %	DM_{12} %
26.0	1.86 (1949)	612	14.9	1.15	2.66
	1.88 (1951)	520	13.2	0.63	1.38
	1.77 (1952)	405	11.8	0.14	0.24
24.0	1.55 (1949)	492	14.5	0.55	1.13
	1.59 (1951)	419	13.3	0.35	0.65
	1.44 (1952)	329	11.7	0.09	0.14
22.0	1.41 (1949)	411	12.9	0.29	0.58
	1.39 (1951)	360	12.9	0.20	0.34
	1.28 (1952)	276	11.8	0.05	0.08
20.0	1.13 (1949)	338	13.1	0.15	0.29
	1.11 (1951)	292	13.1	0.11	0.19
	1.00 (1952)	216	11.9	0.03	0.04

Table 7. Comparison of in-bin solar corn drying for different bin depths in Columbia, Missouri. Drying conditions are listed in Table 1.

Bed depth ft	Rad x 10^5 BTU/ft^2	Time hr	MC_{av} %wb	DM_{av} %	DM_{12} %
10.0	1.19 (1949)	409	13.0	0.29	0.57
	1.18 (1951)	356	12.9	0.20	0.35
	1.02 (1952)	269	11.9	0.05	0.08
12.0	1.42 (1949)	411	12.9	0.29	0.58
	1.39 (1951)	360	12.9	0.20	0.34
	1.28 (1952)	276	11.8	0.05	0.08
14.0	1.66 (1949)	411	12.8	0.29	0.58
	1.64 (1951)	358	12.7	0.20	0.35
	1.48 (1952)	275	11.7	0.05	0.08
16.0	1.90 (1949)	410	12.8	0.30	0.58
	1.88 (1951)	356	12.7	0.20	0.35
	1.64 (1952)	276	11.7	0.05	0.08

Table 8. Comparison of in-bin solar and non-solar corn drying for different airflow rates in 1951 in Columbia, Missouri. Drying conditions are listed in Table 1 (except for solar collector = 0.175 ft^2/bu).

Airflow rate cfm/bu	Rad x 10^5 BTU/ft^2	Time hr	MC_{av} %wb	DM_{av} %	DM_{12} %
0.5	1.13	1848	13.5	0.74	1.49
	N.S.	2873	15.1	0.77	1.39
1.0	0.74	1032	14.7	0.39	0.72
	N.S.	1320	14.9	0.42	0.74
1.5	0.56	666	14.7	0.29	0.51
	N.S.	780	15.1	0.30	0.53
2.0	0.46	504	13.9	0.23	0.39
	N.S.	588	14.8	0.24	0.40
2.5	0.39	413	14.1	0.20	0.33
	N.S.	456	14.5	0.20	0.33
3.0	0.35	359	14.0	0.17	0.28
	N.S.	393	14.2	0.18	0.29

Table 9. Comparison of in-bin solar and non-solar (N.S.) drying for different starting dates in Columbia, Missouri. Drying conditions are listed in Table 1.

Starting Date	Rad x 10^5 BTU/ft^2	Time hr	MC_{av} %	DM_{av} %	DM_{12} %
Sept 1	N.S. (1949)	1252	14.9	0.47	0.79
	1.80 (1949)	449	13.9	0.22	0.43
	N.S. (1951)	815	13.9	0.48	0.85
	1.49 (1951)	388	13.1	0.33	0.64
	N.S. (1952)	435	13.8	0.24	0.53
	1.43 (1952)	270	12.1	0.16	0.36
Sept 15	N.S. (1949)	1198	14.9	0.32	0.48
	1.63 (1949)	341	12.7	0.20	0.34
	N.S. (1951)	687	14.0	0.23	0.46
	1.57 (1951)	324	12.9	0.15	0.30
	N.S. (1952)	408	12.6	0.15	0.26
	1.44 (1952)	287	11.9	0.13	0.24
Oct 1	N.S. (1949)	698	14.8	0.38	0.63
	1.42 (1949)	411	12.9	0.29	0.58
	N.S. (1951)	588	14.8	0.24	0.40
	1.39 (1951)	360	12.9	0.20	0.34
	N.S. (1952)	386	13.0	0.05	0.07
	1.28 (1952)	276	11.8	0.05	0.08
Oct 15	N.S. (1949)	768	14.0	0.16	0.25
	0.42 (1949)	647	13.9	0.14	0.24
	N.S. (1951)	792	14.7	0.14	0.21
	1.33 (1951)	574	14.0	0.12	0.20
	N.S. (1952)	380	11.9	0.03	0.06
	1.27 (1952)	287	11.1	0.04	0.07
Nov 1	N.S. (1949)	696	13.9	0.08	0.15
	--	---	----	----	----
	N.S. (1951)	887	14.0	0.06	0.11
	1.44 (1951)	664	13.9	0.05	0.10
	N.S. (1952)	475	13.8	0.05	0.09
	1.05 (1952)	372	13.1	0.05	0.08

Fig. 1. Average moisture content during in-bin solar corn drying at standard conditions with three different collector sizes.

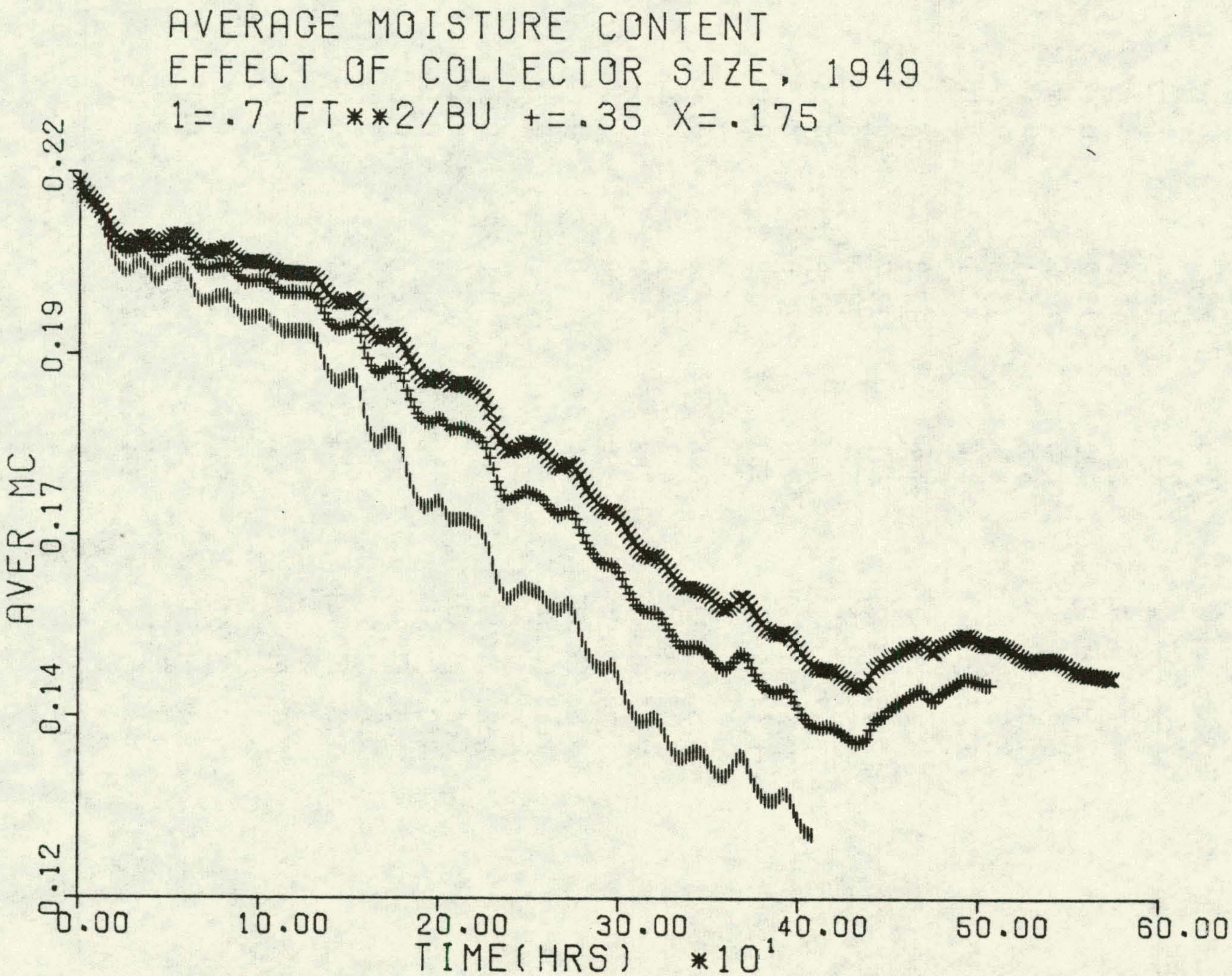


Fig. 2. Moisture content at top of the bin during in-bin solar corn drying at standard conditions with three collector sizes.

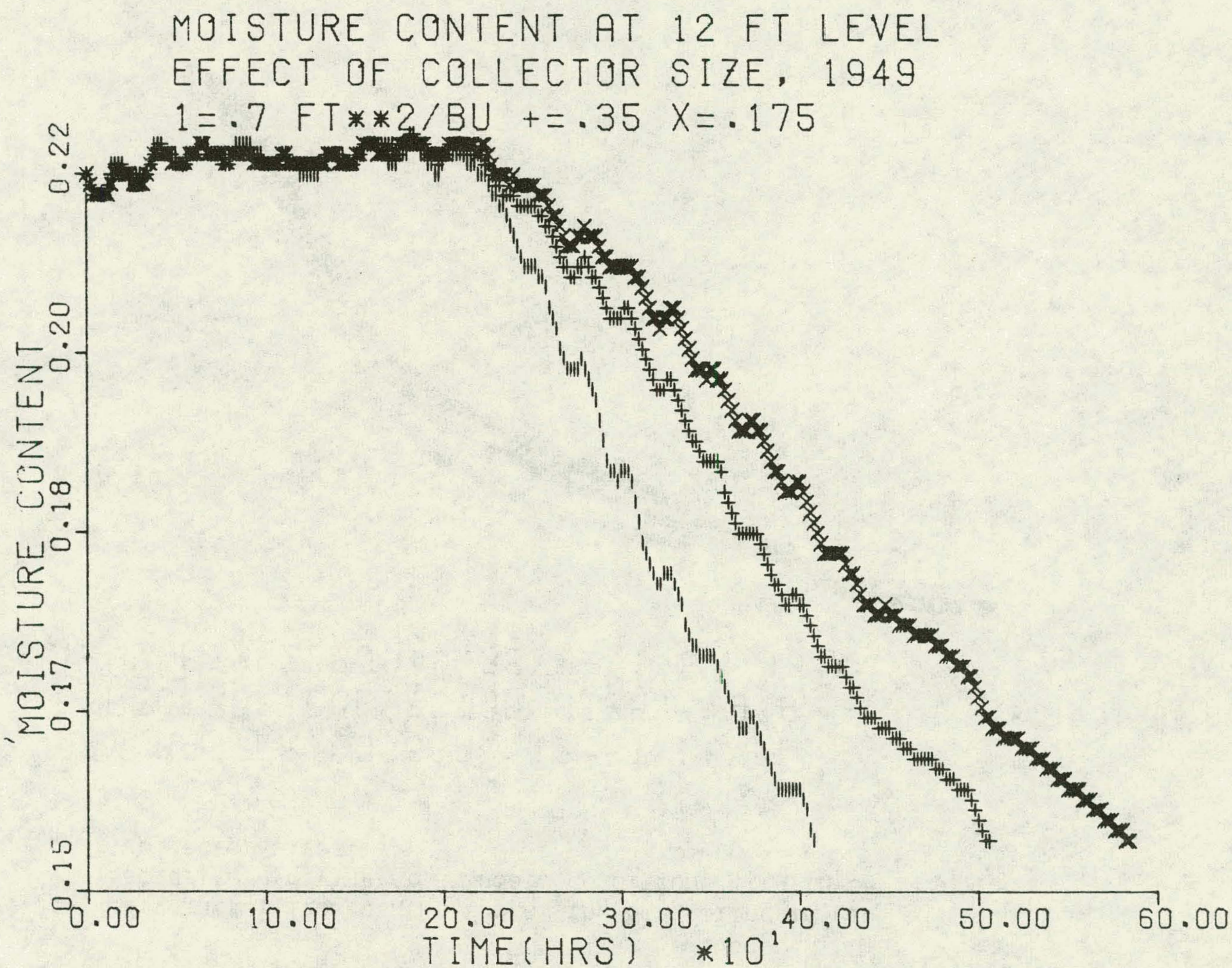


Fig. 3. Dry matter loss at the top of the bin during in-bin solar corn drying at standard conditions with three collector sizes.

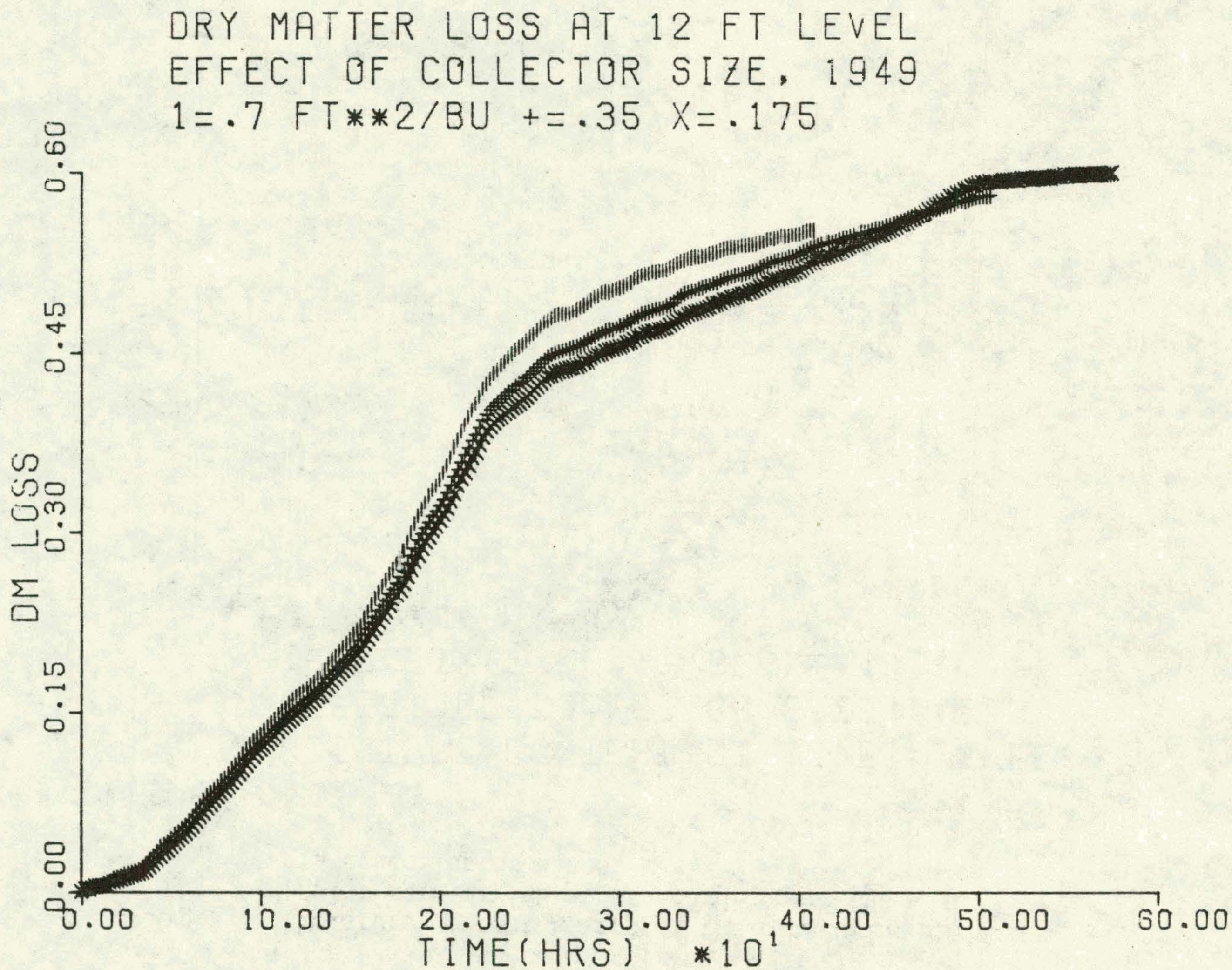


Fig. 4. Dry matter loss at the tops of the bin during in-bin solar and non-solar (natural air) corn drying at standard conditions in 1951.

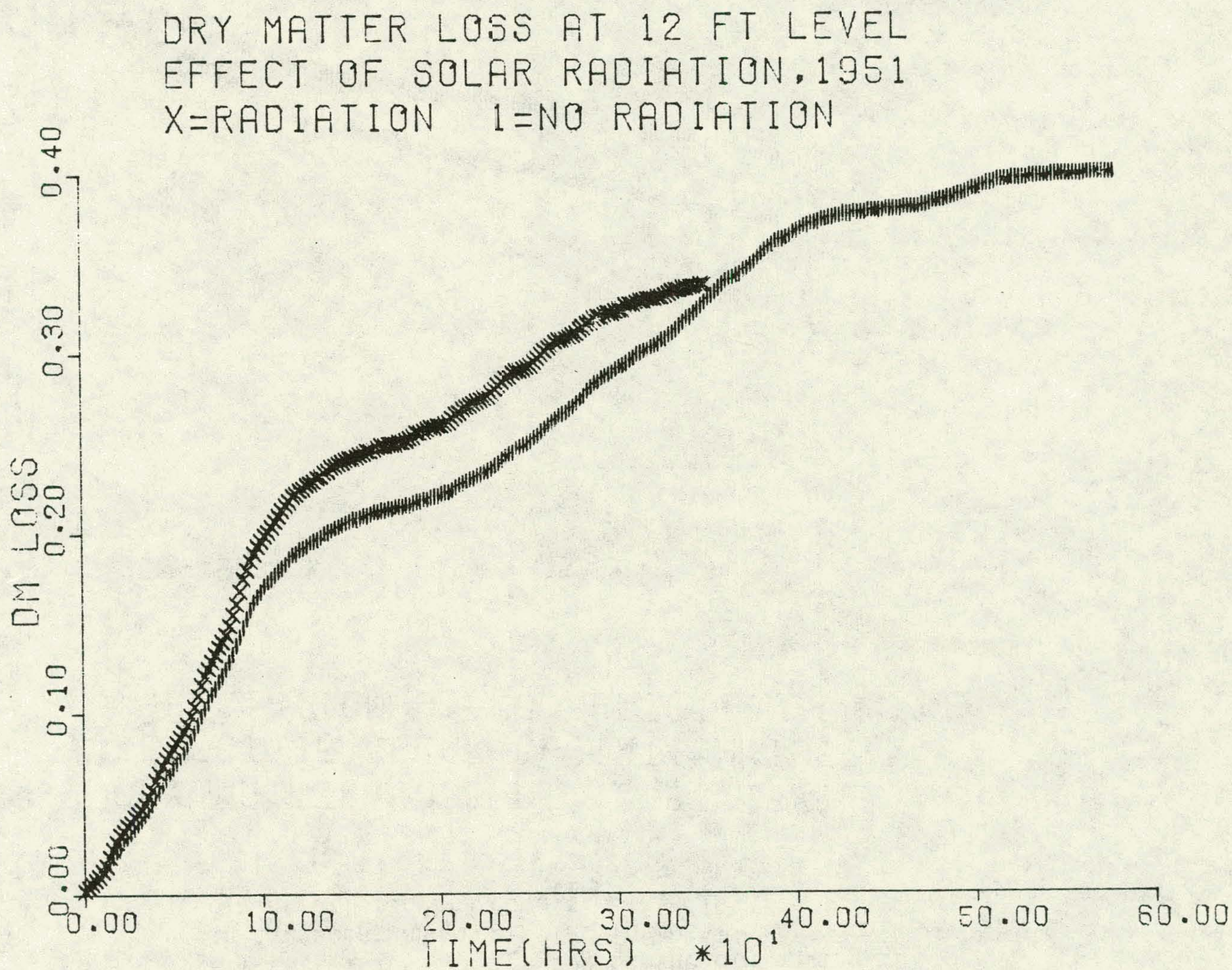
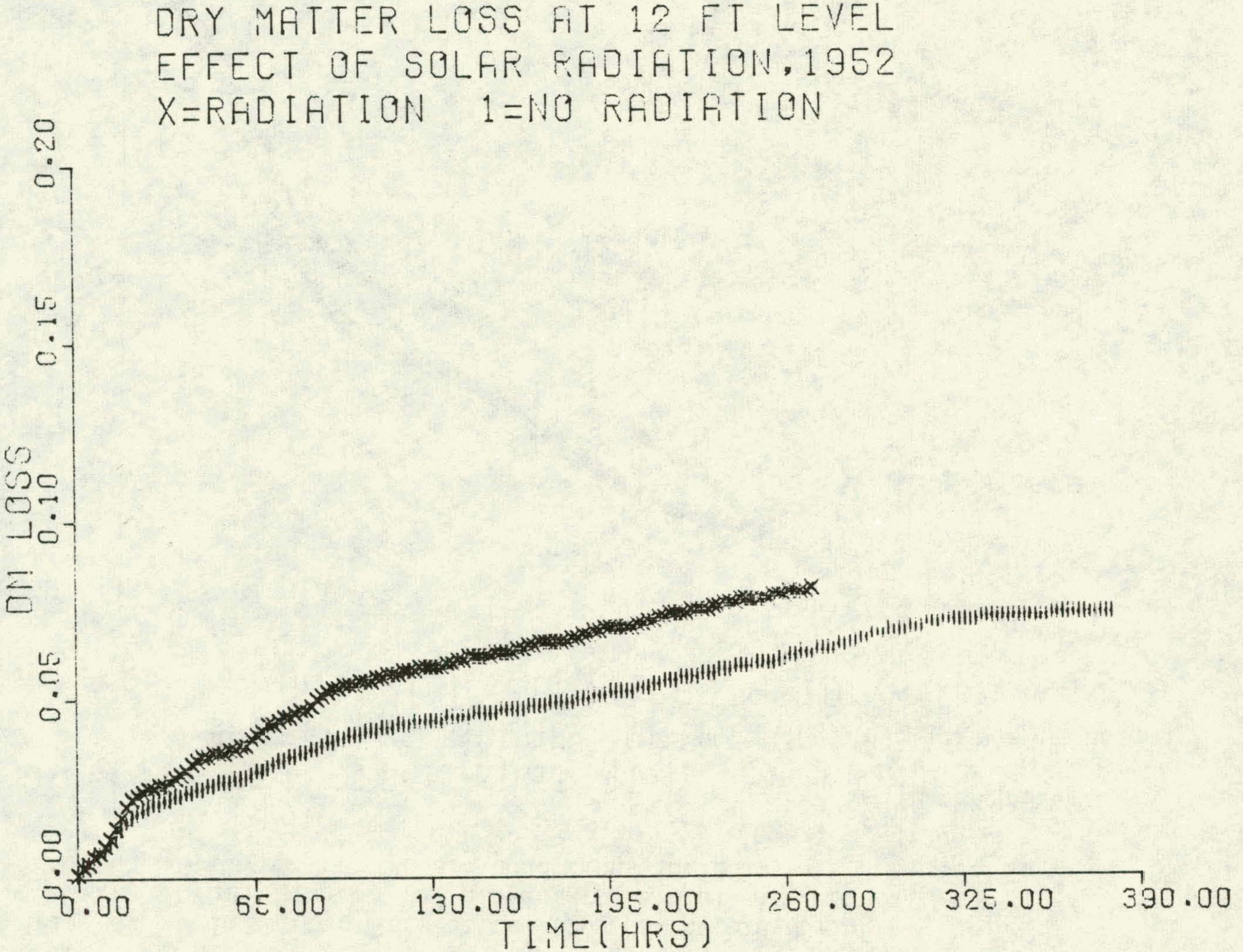


Fig. 5. Dry matter loss at the top of the bin during in-bin solar and non-solar (natural air) corn drying at standard conditions in 1952.



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