J. Separ. Proc. Technol., 4 (4) 15–22 (1983)

© Copyright, Chaldwall University Press Ltd.,
P.O. Box 68, London, NW11 0PG, England

PN-AAW-993
44912.

COMPARISON OF PORTABLE AND STATIONARY CROP DRYERS FOR DEVELOPING COUNTRIES

*C. C. Smith,**
Solar Energy Applications Laboratory,
Colorado State University,
Fort Collins, CO 80521,
U.S.A.

and

V. R. Muthuveerappan,
Annamalai University,
Annamalainagar 608 002,
Tamil Nadu,
India.

This paper reports the results of a comparison between stationary and portable solar crop dryers for developing nations. The overall utility, that is, drying performance combined with the annual duty period under actual practice, has been investigated using the two schemes. The dryers utilize about 40 m² of flat plate solar collector to dry approximately 1 ton per day of harvested crop. Fans are used in all but one design to move air through the collectors and the grain dryer. The drying of paddy in South India was taken as the crop and location for the study. The stationary unit was designed to serve approximately 40 farmers at one village location. The solar collectors were integrated into the roof structure of a rice mill building at a 20° tilt. In addition to harvested paddy drying, the stationary solar dryer is used to dry parboiled rice during non-harvest periods, thus increasing the annual duty on the solar equipment. The portable system incorporates different materials to allow for portability, but it is designed to provide comparable drying yield. The portable dryers have a potential for high annual duty by moving in response to the drying needs in a region.

INTRODUCTION

A demonstration solar crop-drying project, supported bilaterally under the Government of India and the United States Agency for International Development funding, has been under way since April 1981. The project is a collaborative effort between two universities, Annamalai University (AU) in India and Colorado State University (CSU) in the United States. Solar crop dryers were developed mainly for application in rural India although many features of these dryers relate to other developing countries as well as developed countries such as the United States.

* Author to whom correspondence should be dressed

Paper presented at the International Symposium on *Energy Savings in Drying Processes — Applications to Industry and Agriculture*, Liege, Belgium, 4–6 October 1983.

Solar crop or food drying has in fact been developed and proven by several investigators around the world over a period of many years[1]. In spite of such development, there are relatively few crop dryers in worldwide use, compared even with other solar devices such as water heaters. It is likely however to gain acceptance once it is convincingly demonstrated that improved drying of the product can be gained at equal or lower cost than with the available alternative drying processes. The AU/CSU project set out to demonstrate that with low-cost local construction coupled with a high annual duty factor, these criteria could be met by solar dryers[2].

DESCRIPTION OF CSU STATIONARY SOLAR DRYER

On the American side of the binational project a stationary 1 ton/day dryer was constructed and demonstrated. More specifically, it was designed to remove about 100 kg of water per day from grains such as rice, barley, or corn. This unit was designed to meet the drying needs of small village mills in India or individual farmers in the United States.

The CSU dryer incorporates a low tilt angle collector into the roof structure of a building suitable as shelter for mill operators, crop storage, or for other functions (see **Figure 1**). By obtaining a dual function from some of the more costly structural materials in this way, added value is realized. Also, in the case of village mill operation, provision has been made for drying both harvested as well as precooked rice. This feature allows much higher annual duty, since the precooking is done at other than harvest times.

HARDWARE DESCRIPTION

Air is solar-heated by passing it twice through thirteen solar collectors in parallel. The thirteen individual collectors measure 0.6 m in width by 4.5 m in length. Each collector is constructed to give two air flow passages as shown in **Figure 2**. Ambient outdoor air enters the upper air passage formed by the absorber plate below and the single glass cover above. The air

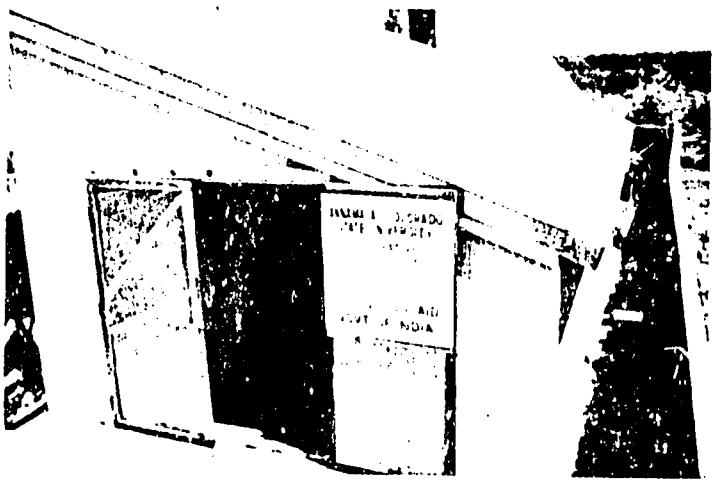


Figure 1.
Exterior view of CSU solar crop dryer; 36.5 m² of solar collector area is integrated into the roof structure of the drying building.

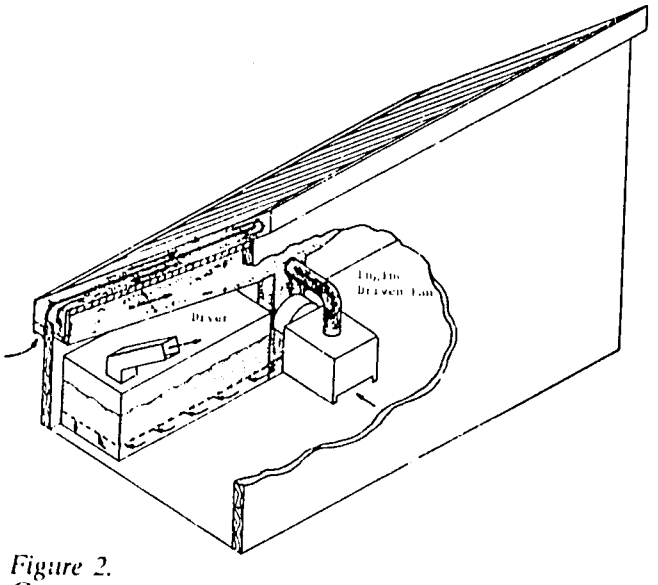


Figure 2.
Cut-away section to illustrate the air flow path.

returns in a lower passage formed by the back insulation below and the absorber sheet above. Each passage thus offers contact between the absorber plate and air to be heated. Both passages are 7.6 cm in depth by 0.60 cm in width. Nominal air flow is 40 l/s in each collector, resulting in a typical Reynolds number of 7000.

The collectors were site-built from basic materials. This was to obtain conditions more like those in developing countries, where such collectors are at present not commonly manufactured, and also because of the dual function of making structural and weather-resistant roofs that also serve as solar collectors.

The structural elements which span the roof and which also provide the structural mainframe of the collectors consist of 1.6 mm thick galvanized steel *U*-shaped channels, 4.8 m in length. The channels are 7.6 cm in depth with 3.8 cm legs. The channels were put in place first and secured to the side walls of the lower structure as is done in normal piece-type roof construction. These were followed by installation of the absorber plates, the glass covers and, finally, the back insulation boards. The absorber plates are of 0.6 mm thick aluminum, coated on the upper surface with an optically selective silicone paint. The glass pieces are 3 mm thick, 0.6 × 1.5 m, with three units per collector panel. The glass was prestressed (tempered) to minimize breakage due to severe winds and snow loads at the site. The glass has a low iron content, giving a high solar transmission. Thermal and optical specifications on the collectors as taken from the manufacturer's literature are given in **Table 1**. The back insulation consists of a high-density fiberglass core, 2.5 cm thick, with a very thin (approximately 0.1 mm) aluminum outer surface. The product is sold in the United States under the general term "fiberglass duct board" and is used in a limited market as an alternative to galvanized steel ducts. The air ducts as well as the collector back material are made of fiberglass duct board (**Figure 3**). The greatest advantages of duct board are high insulation value at low cost and also ease of installation and changing compared with galvanized steel. The disadvantage is its susceptibility to damage.

Table 1
Solar collector optical and thermal specifications

Glass transmission	0.92
Absorber absorptivity	0.95
Absorber emissivity	0.40
Thermal transmission of back insulation (MJ/hr·°C·m²)	0.0025

Figure 3.
Interior view showing air ducts, dryer and computer data unit; a fan is behind computer.

The dryer itself is a rectangular compartment 1.14 m wide by 2.92 m long by 1.2 m high. It is constructed of 3.8 cm thick walls, consisting of 0.8 mm thick galvanized steel on both sides of a styrene board core. Air entrance and distribution is provided below the grain by a wire mesh having 3 mm spacing and supported on

γ

concrete blocks. Air is forced upward through the grain which varies in depth between 40 and 60 cm depending on moisture content and, of course, quantity of loading. The air is exhausted out on the opposite side of the building (**Figure 2**).

Figure 4.
Three stirring augers are driven by gear motors travelling on a bridge over the grain.

Mechanical stirring was introduced during the second year of operation in order to mix the grains. **Figure 4** is a photograph illustrating the use of this device. Three stirring augers are driven independently by three gear motors with variable speed range of 0 to 60 rpm. The augers are supported by a travelling bridge which traverses the length of the dryer. The speed of travel is determined by a fourth gear motor driving a cable winch at between 0 and 1 meter per minute. The total electrical energy for stirring is about 0.1 Kwhr/ton (1 watt hour per kg water removed).

The fan is a forward-curved centrifugal unit with a fan wheel diameter of 38 cm. The fan characteristic for the specific application yields approximately 500 liters per second at a pressure of 10 kPa and a nominal power requirement of 1 kw. During the first year of operation the fan was driven by a 0.75 kw electric motor. In the second year the fan was fitted with a nominal 2.25 kw natural gas engine. The engine is derated to approximately 1.5 kw due to high elevation, and is thus operated at about one half load to provide the equivalent of 0.75 kw for fan power. The engine is equipped to take advantage of wasted heat from both the exhaust and the engine air-cooled surfaces. A housing has been built around the engine and also a heat exchanger on the exhaust gas pipe. Air is drawn through this housing and into the main air duct from the collectors. Thus the waste heat from the engine is combined with that from the solar collectors for delivery to the dryer.

DESCRIPTION OF THE DESIGN

It was predicted from the analyses of others[3,4] that a solar system with 36 m^2 of collector area is capable of drying one dry ton per day of grain from an initial moisture content of 20% to a final moisture content of 13% during the July to September season at Fort Collins, Colorado. That is, from 250 kg of water to 150 kg. This was generally the case during the first year. On days of cloudy weather a second day was required to accomplish this amount of drying, and on very clear days the drying was completed by mid-afternoon.

The drying process begins within one hour after sunrise and proceeds to within one hour of sunset or when the product moisture reaches 12% (WB). On a few occasions air flow was extended beyond sunset to cool the grain and provide more uniform drying. The air flow is adjusted to between 300 to 500 l/s. This air volume maintains a proper balance of energy removal in the solar collectors, ranging in a temperature rise of the air of between 10 and 30 °C.

EVALUATION OF PERFORMANCE

The energy performance of this device can be viewed in different ways, and thus the results are presented from different perspectives. The simple evaporation energy to separate water from the grains is normally complicated by factors of lost heat and also by sensible heating or cooling of the grain mass. In addition, one must consider the ambient condition of the air and the rate of water removal. For example, farmers typically dry harvested grains in Colorado by natural air drying at slow rates due to low ambient humidity using only fan energy of less than 1 MJ per kg H_2O.

In a sense, the environment offers an energy contribution to drying whenever the relative humidity is below the equilibrium relative humidity of the material to be dried. Thus the energy associated with reduced ambient relative humidity has been reported, as well as the applied energy consisting of solar, fan, and stirring energy.

Since the energy input also affects the rate of moisture removal, this rate is also given. Finally, it is of interest to state the specific performance of the collectors, such as m^2 of collectors per kg of water per day. This factor clearly is to be associated with the solar radiation at the testing location so that it may be extended to applications in other climatic locations.

EXPERIMENTAL RESULTS

The testing of both AU and CSU dryers is conducted using a computer-controlled data acquisition system (**Figure 3**). Measurements are taken every 36 seconds, and include solar radiation, air flow rate, four dry-bulb and two wet-bulb temperatures. The small, 32 K computer calculates the energies and water amounts also every 36 seconds and adds together these numbers throughout the testing period of up to sixteen hours. The computed data is displayed every six minutes on a paper tape format as shown in **Figure 5**. This feature provides information feedback to the test operator such that questionable data can be investigated promptly during the test. Apart from the simple conversion of units and summation of data as just described, the computer is programmed to compute the constant moisture and pressure rate of energy (power) supplied to the air as:

$$\text{Power} = \text{Specific heat} \times \text{Mass flow} \times \text{Difference of temperature}$$

In addition, the moisture content and relative humidity of the air, given the wet- and dry-bulb temperatures, are computed using the following equations fitted to the Mollier chart for 5000 ft. elevation:

$$X_s = 0.00485 + 0.000219 \times T_{wb} + 0.0000216 \times T_{wb}^2$$

$$X = X_s - (T - T_{wb}) \times (0.24 + 0.441 \times X_s)/(597 + 0.441(T - T_{wb}))$$

3

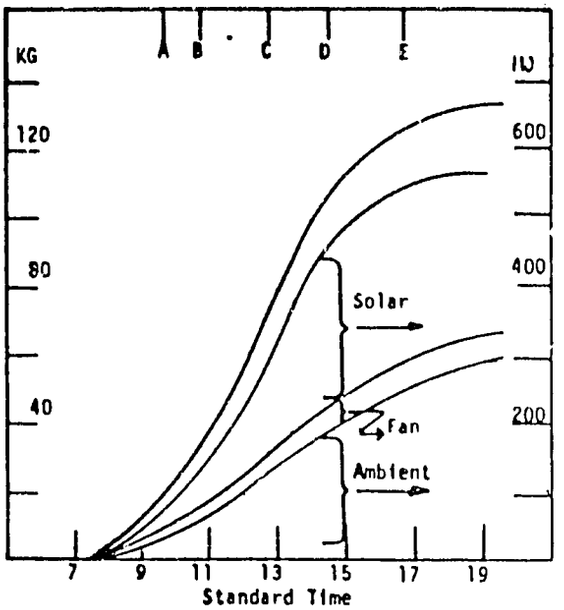


Figure 5.
Sequence of water removal and applied energy during a typical solar dryer test at CSU (17 August 1983).

where T = dry-bulb temperature (°C); T_{wb} = wet-bulb temperature (°C); X_s = saturation moisture ratio at T_{wb}; X = moisture ratio at state point (T, T_{wb}).

Finally, the accumulated energy input to the fan engine was taken by volumetric measurement of fuel.

Table 2 is a summary of energy inputs, water removal and specific performance factors obtained for ten drying tests at CSU. The average for all tests is given below the listing of the ten tests.

Energy inputs include solar heat, mechanical energy for stirring and the fan, and also an assumed contribution of heat from the ambient air. This ambient energy is taken as the sensible heat required to bring the air at constant moisture and pressure from the saturated state (dew point) up to the ambient temperature. Hence, "applied" energy is reported to be the actual sum of solar plus mechanical energy, and "total" energy refers to the applied plus the ambient contribution. One may view the total as a "worst condition" requirement for energy with the ambient relative humidity always at 100%.

From **Table 2** it is possible to evaluate both the dryer and the solar energy system independently. For example, one can see from the averages that the dryer requires 2.6 MJ/kg to remove water at the rate of 63 kg per day, and that the overall efficiency of the solar system to deliver energy to this dryer is 49.7%. Finally, one can see that it requires 0.45 m^2 of solar collector area to remove 1 kg of water per day for the total system with average solar radiation of 9.9 MJ per m^2 per day.

It is to be noted that these quantities reported 'per day' refer to operating hours only. Total daily solar radiation at the test site in July averages nearly twice this amount, or 18 MJ per m^2 per day.

It should be further noted that such a solar system without energy storage delivers the energy to the dryer at a variable rate. Thus the rates are presented per day rather than per hour, since the hourly rate is not steady. **Figures 5 and 6** are an attempt to illustrate the development of the drying process during a typical solar day. In **Figure 5** the removal of water is shown in sequence with delivery of energy. In **Figure 6** the air heating and dryer

Table 2
Results of ten solar drying tests

Date (1983)	Energy ambient[1]	Input mech[2]	Solar (MJ/day)	Collector area (m^2)	Solar radiation (MJ)	Collector efficiency	kg H_2O/day removed	Specific energy applied (MJ/kg)[3]	Specific energy total (MJ/kg)[4]	Specific solar performance (m^2/kg/day)[5]
26/7	66	8	129	36.5	280	46	46.7	2.9	4.3	0.77
27/7	74	8	154	36.5	275	56	57.8	2.8	4.1	0.63
29/7	133	18	258	36.5	398	64	89.9	3.0	4.5	0.40
3/8	49	20	130	36.5	317	41	47	3.2	4.3	0.77
4/8	55	19	170	36.5	404	42	60.6	3.1	4.0	0.63
5/8	75	14	92	19.6	224	41	47.1	2.3	3.8	0.42
11/8	38	13	114	19.6	223	51	43.3	2.9	3.8	0.45
15/8	120	12	221	36.5	402	55	90.4	2.6	3.9	0.45
16/8	154	18	125	19.6	201	44	80.1	1.8	3.7	0.25
17/8	118	31	107	19.6	187	57	67.2	2.0	3.8	0.31
Av.	88	16	150		9.9	49.7	63	2.6	4.0	0.45
%	35	6	59		(MJ/m^2/day)					

[1] Ambient energy refers to the hypothetical contribution of energy to heat the air from saturation (dew point) up to the ambient condition.
[2] Mechanical energy included fan and stirring energy required.
[3] Applied energy is the total of solar and mechanical.
[4] Total energy includes ambient, mechanical, and solar energy.
[5] Specific solar performance is given as the square meters of gross collector area employed per kg of water removed during the day-long test.

4

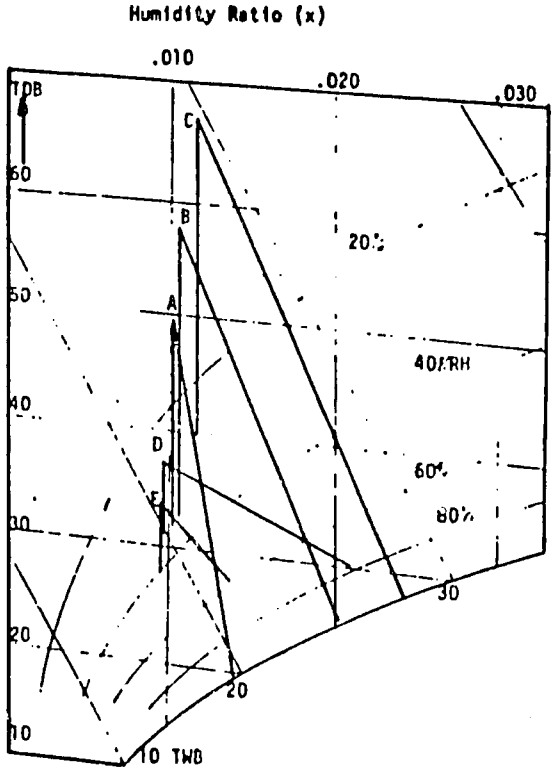


Figure 6.
The path of air states at time points (A through E) on a Mollier diagram.

evaporation processes are shown on the Mollier diagram for water in air. Five paths are shown in **Figure 6** which refer to the time points A through E in **Figure 5**. The paths taken by the air states show in **Figure 6** how the solar drying process is ever changing. One can observe from this sequence the effect of variable solar energy and also the factor of sensible heating and then cooling of the grain mass. Normally it is important to continue cooling the grain even after sunset in order to capture the sensible heat of the grain and employ it to further evaporate water.

COST OF THE CSU SOLAR DRYER

Table 3 presents a cost breakdown for the major elements of the CSU solar dryer. The cost of the building structure is excluded from the final figure of investment cost per kg water removed per hour since it is not essential to drying. The cost of a development pilot scale plant should, of course, not be taken as a firm projection of wide-scale commercial cost. On the one hand the cost of overhead and profit are excluded, while on the other hand there is inefficiency in constructing the first of a kind.

DESCRIPTION OF ANNAMALAI PORTABLE SOLAR DRYERS

On the Indian side an investigation was undertaken to demonstrate the operation of one ton per day portable solar dryers. Three types of dryers were constructed using polyethylene plastic collectors: a static deep bed dryer with an engine-driven fan (**Figure 7**), two intermittent flow-column type dryers with engine-driven fan, (**Figures 8 and 9**) and another static bed dryer utilizing natural convection (a photograph is not available).

Table 3
Cost breakdown (U.S. $)

Collectors		
glass	400	
steel	105	
aluminum	195	
back insulation	122	
absorber paint	50	
other materials	40	
	912	
labor (5 man days)	483	
Total	1392	($38.50 per m²)
Dryer including ducts and equipment		
steel	200	
screen	28	
fan	280	
ducts	80	
other material	20	
	608	
labor (4 man days)	320	
Total	928	
Total for solar dryer	2320	
Main structure (34 m²)		
concrete	730	
wood frame materials	780	
	1510	
labor (10 man days)	800	
Total	2310	
Grand total	$4630	

Specific investment cost = $2320/63 kg per day
= $37/kg per day

The collectors are of inflated plastic, 2 meters wide and 20 meters long. The earth under this area is prepared to be even, with trenches dug two meters apart to secure the plastic edges. A transparent

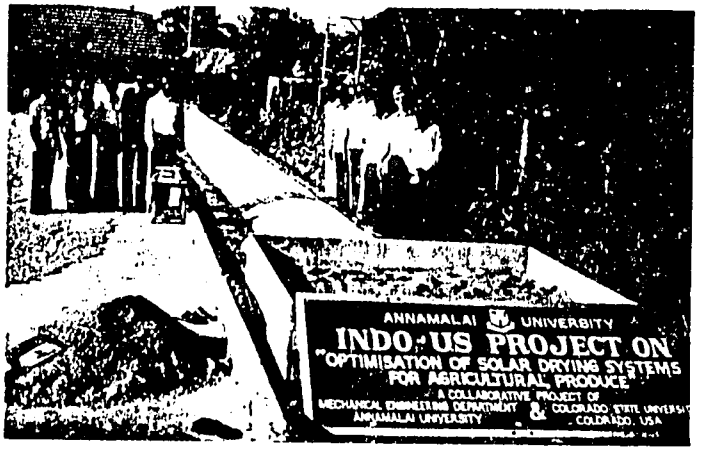


Figure 7.
Static bed dryer showing 2 × 20 m inflated plastic collector; grain is stirred by walking.

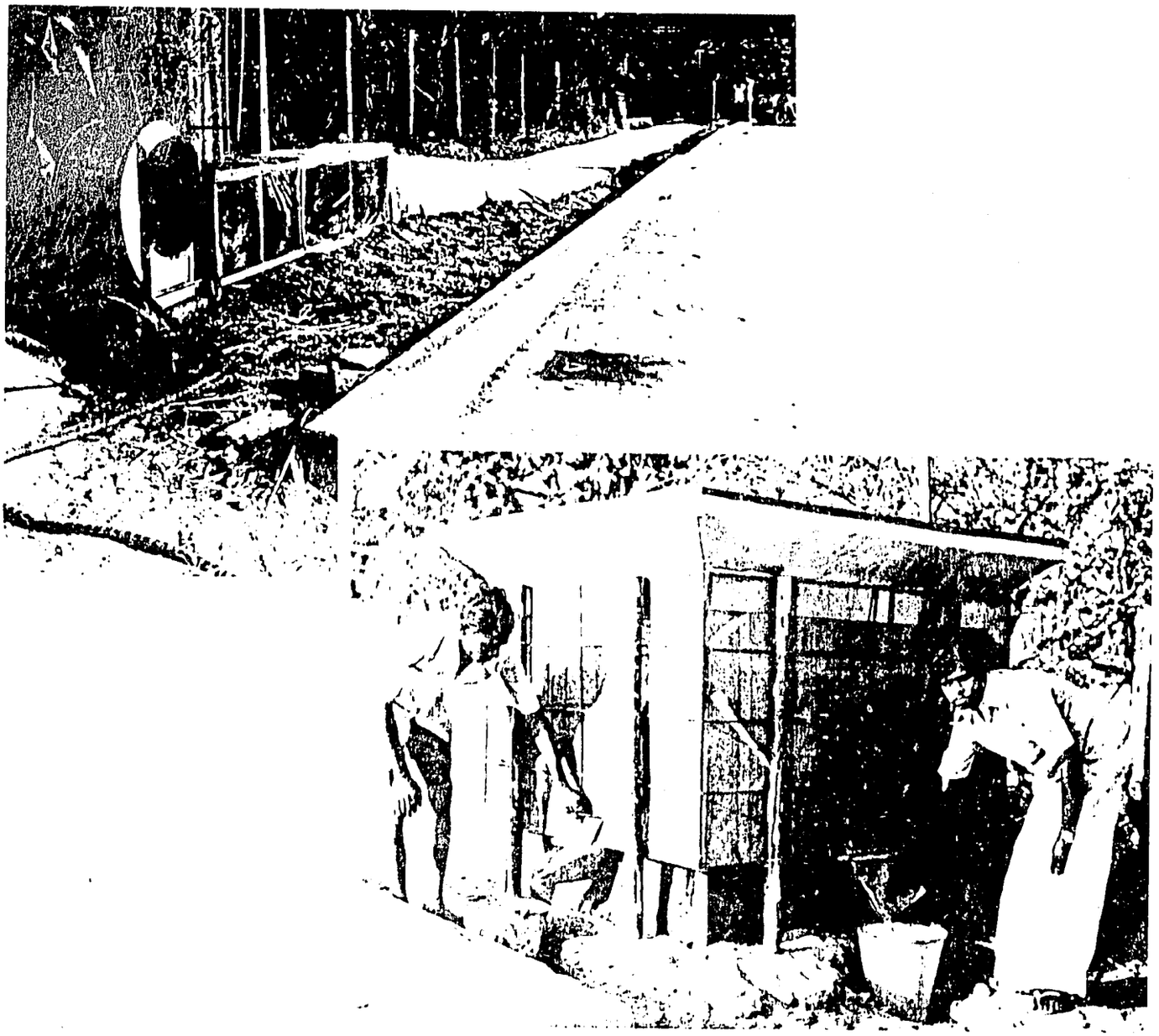


Figure 8.
Low elevation column dryer showing engine fan, collector and unloading.

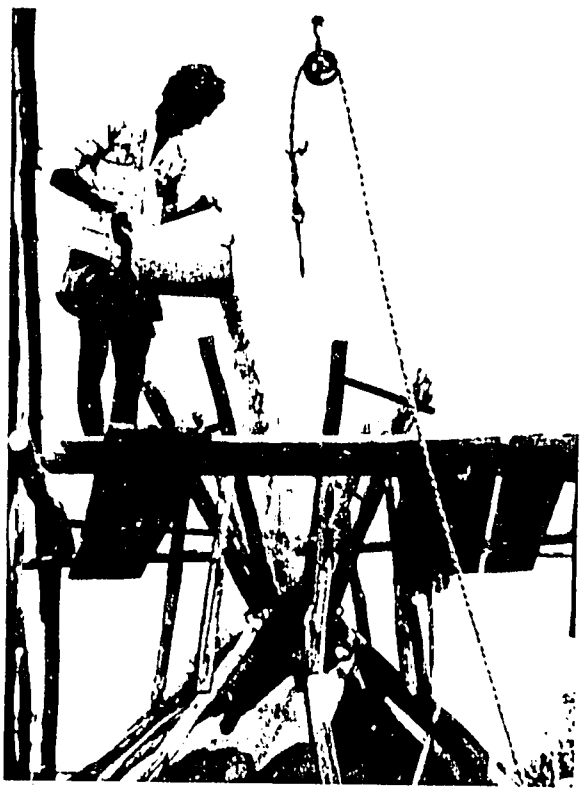
polyethylene sheet is then laid over a black sheet and rolled onto wooden poles in the trenches as shown in the illustration of **Figure 10**. Finally, the trenches are filled back over the poles to give an airtight edge seal.

Functionally, the portable dryer achieves the same objective as the stationary dryer at CSU of increasing the annual duty factor. The portable dryers are taken down at one site and erected at another in response to the need for drying at different but nearby locations. The drying performance is somewhat less, nominally drying 1/2 to 1 ton of paddy per day with 40 m^2 of collector area compared with 1 ton per day using less area at CSU. This is understandable due to the higher ambient humidity in South India and also to the use of lower grade collector materials. The use of cheaper materials and portability demand somewhat more labor input. This is a practical balance, however, in a developing country where labor is relatively cheaper than materials. Also grain stirring and handling are done manually in the Indian project, rather than mechanically as in the U.S., for the same reason.

AU DRYER OPERATION

Static bed. This unit is of 600 kg per day capacity, utilizing a blower of 1320 l/s capacity. The blower is connected to a solar collector of size 19 m × 1.5 m, which in turn is connected to a shallow-bed dryer. The dryer's size is 2.7 × 2.4 m, and made of wooden planks and mild steel perforated sheets. The entire setup is shown in **Figure 7**.

Experiments were carried out in the static-bed solar dryer during January–February 1983. Paddy was dried in two batches, each batch was loaded into the bin and dried for half an hour.



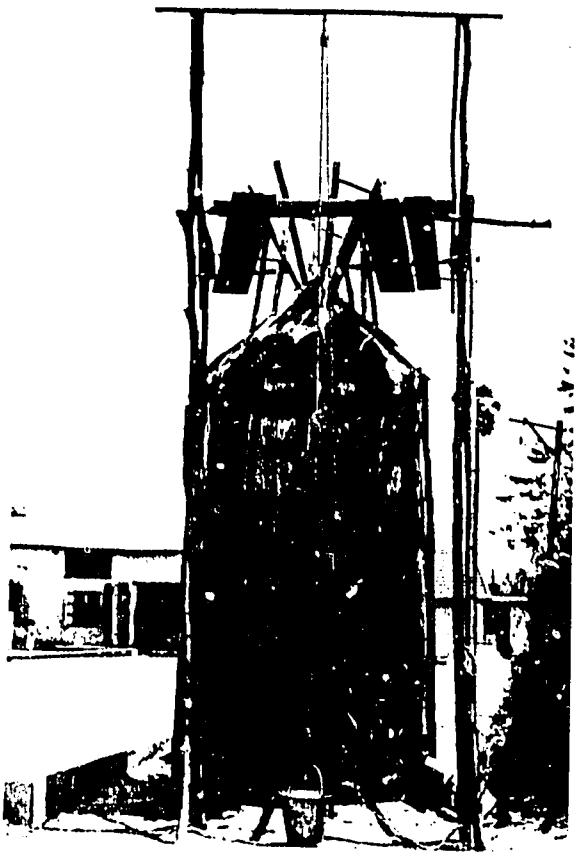


Figure 9.
High elevation column dryer constructed of screen wire and native wood poles; dryer is loaded manually with the aid of bucket and rope.

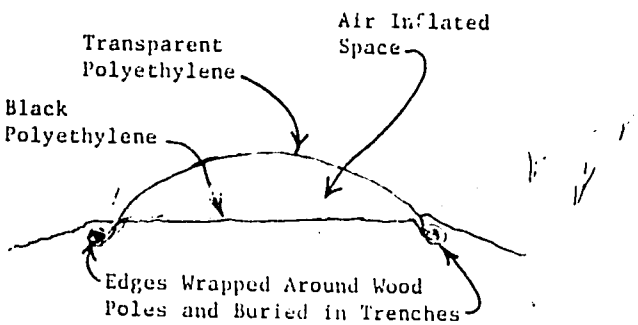


Figure 10.
Cross-section illustration of Annamalai University air-inflated polyethylene collectors.

Vertical column. In order to overcome the difficulty of turning the grain during drying in a static-bed dryer, a vertical-column recirculated dryer is used. On an average, 500 kg of paddy was dried during the month of July 1983 in about 4 hours. During this time paddy was recirculated manually once every half hour. Another 500 kg of paddy was dried for the rest of the day. The collector is 30.5 m long and 2.1 m wide. A 1320 l/s blower forces the air through the polyethelene collector. Another blower of the same capacity draws air from the collector and forces it into a vertical column-screen dryer through a diffuser. The spacing between the screens is kept at 15 cm. The height is kept at 150 cm so that manual recirculation is possible. The entire setup is shown in **Figure 8**.

EXPERIMENTAL RESULTS

Static bed. The energy demand to evaporate water from the grain was 2.38 MJ/kg water. The power required to drive the fan amounted to 0.26 MJ/kg, and thus the total energy used was 2.64 MJ/kg. The specific solar performance was 0.12 kg of water removed per

MJ of incident solar energy. The collector efficiency ranged from between 30 to 40%.

Vertical column. The efficiency of the collector was again in the range of 30 to 40%. The energy demand to evaporate water from the grain was 2.41 MJ/kg of water. Electric power required to drive the fan amounted to 0.27 MJ/kg, and thus the total energy was 2.78 MJ/kg. The specific solar performance was 0.136 kg of water removed per MJ of incident solar energy.

COST OF THE AU SOLAR DRYER

The cost of the AU solar dryer is approximately U.S. $500, excluding the cost of two blowers. The operation cost for drying one ton per day is $0.36 for fan power. This might be reduced to half with a properly sized fan. Two workers are required to set up and operate the dryers. In fact, two workers could just as well manage two or more such dryers to reduce unit costs.

Hence, under the above conditions the revised operational cost will work out to $1.35 per ton. This is comparable to the cost of present-day openyard drying in India. Though the advantage by way of cost of operation is the same as that of openyard drying, the improved outturn of rice due to uniform drying in this solar dryer will definitely fetch sizable returns to the farmers and the rice millers.

CONCLUSIONS

Experience over a two-year period has shown that both stationary and portable schemes are workable in actual drying practice. The overall performance of the stationary dryer is higher with respect to solar energy receiving area. This is to be expected due to the higher grade materials used in the stationary collectors. In a developing country economy, such as rural India, where cost of materials is relatively high compared with other resources (principally labor), the portable dryer performance loss would be offset by the savings in material costs. At a congested mill site, however, reduced area as well as the roof integration design may be necessary.

Annual duty, a primary factor in overall value of the devices, could only be determined as the maximum possible for each scheme. Whether or not this maximum duty is to be realized would depend heavily upon management and siting of the plants. The portable scheme has an estimated potential of 80% annual duty, allowing a 20% loss of time for handling and transporting the equipment. Clearly this potential utilization would require excellent judgment on the part of the operator to see that his unit was on hand at the right location for operation throughout the year.

The stationary scheme holds the potential for higher annual duty, estimating only 10% loss of time needed for possible repairs. The stationary plant duty could, however, be much lower than the portable plant if the stationary site were not serving a more or less year-round need. Therefore, stationary plant siting becomes critical in the assessment.

Based upon a utilization of 200 days per year, it is estimated that either of these dryers could pay back the original investment in three to five years. More precise estimates would require a first-hand knowledge of conditions and costs to be incurred at a specific location and for a specific service. Perhaps more important than to gather up such precise figures is to project the future cost trends of labor and material inputs as opposed to the energy and grain losses being spared. Despite unprecedented fuel cost increases, these trends have not been favorable for solar energy drying in the United States. With a view toward indigenous sources of labor and materials, however, it is likely that the reverse trend is forthcoming in developing countries.

REFERENCES

1. *Sunworld*, International Solar Energy Society, 4 (6) 1980.
2. Brown, Norman L., *Renewable energy resources and rural applications in the developing world*, 1978 by American Association for the Advancement of Science, pp. 27–43.
3. *Energy conservation — the European masters effort*, Master Brewers of America Technical Quarterly, 16(2) 68–72 (1979).
4. Geeraert, B., *Minimum Available Energy Demand for Drying*, Proceedings of a Conference on Energy Savings by Drying Processes 27–30 October 1982, Université de Liège, Liege, Belgium.