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ANALYSIS OF TWO COMMERCIAL RICE-DRYING SYSTEMS UNDER MALAYSIAN CONDITIONS

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ANALYSIS OF TWO COMMERCIAL RICE-DRYING SYSTEMS UNDER MALAYSIAN CONDITIONS

By

Hussain Bin Mohd. Salleh

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ABSTRACT

ANALYSIS OF TWO COMMERCIAL RICE-DRYING SYSTEMS
UNDER MALAYSIAN CONDITIONS

By

Hussain Bin Mohd. Salleh

A perennial problem of the Malaysian rice industry is the inadequate drying capacity of the dryers for properly handling bumper harvests and very wet grain at the private and public rice mills

The concurrentflow (CCF) dryer and the in-bin counterflow (IBCF) dryer, both used at commercial elevators in the U.S., were evaluated for application in Malaysia.

Field experiments were conducted with the multi-stage concurrentflow dryer and with the in-bin counterflow dryer. The Michigan State University (MSU) concurrentflow and in-bin counterflow drying models were validated with the experimental data. The drying of rice under Malaysian conditions in both dryers is simulated using the appropriate MSU simulation models. In drying rice in Malaysia from 23 % to 13.5 % (without cooling) in three passes (i.e. 23-19 %, 19-16 %, and 16-13.5 %), under optimum grain-quality conditions, the three-stage concurrentflow and in-bin counterflow dryers have drying

capacities of 1.023 and 0.026 t/m^2/h, respectively. The predicted energy efficiency is 3861 kJ/kg for the concurrentflow dryer and 6408 kJ/kg for the in-bin counterflow dryer; the maximum inlet air temperatures are 126.7°C and 47.2°C for the two dryers, respectively.

Eight drying systems are proposed for Malaysia to serve 3,000 ha of rice production; double cropping is practiced. A life-cycle costing program was used to evaluate the savings of the systems compared to custom-drying the wet rice at the locally charged price. Each drying system shows a positive cash flow every year over the 11 years of the systems' lifespans.

The IBCF36/1 system (i.e. five 36ft (10.97m) diameter in-bin counterflow dryers located at one site) generates the maximum after-tax total savings, followed by the CCF12/1 system (i.e. one 12ft (3.66)m x 12ft (3.66m) three-stage concurrentflow dryer located at one site). The IBCF18/20 system (i.e. twenty 18ft (5.48m) diameter in-bin counterflow dryers located at twenty separate sites) has the lowest savings compared to custom-drying. On the whole, centralized drying systems cost less, and hence have higher after-tax total savings than decentralized systems.

A multi-stage concurrentflow dryer offers efficient drying and has the least space requirement. However, it demands extensive technical expertise to operate effectively, a definite disadvantage in Malaysia.

In conclusion, it is recommended that for technical as well as economical reasons, the in-bin counterflow dryer is the rice dryer of choice in the 1990s for rice-milling plants in Malaysia.

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TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

Table Page

Table		Page

Table		Page

LIST OF FIGURES

LIST OF SYMBOLS

c	Specific heat, kJ/kg°C
CCF	Concurrentflow
D	Depth, m
E	Electrical energy, kJ
G	Dry weight flow rate, kg/h-m^2
H	Humidity ratio, kg/kg
h	Enthalpy, kJ/kg
h_{fg}	Heat of vaporization, kJ/kg
IBCF	In-bin counterflow
M	Moisture content, % wet basis
M_e	Equilibrium moisture content, decimal d.b.
MR	Moisture ratio, $(M-M_e)/(M_o-M_e)$
p	Pressure, kPa
Q	Airflow rate, m^3/s/m^2
rh	Relative humidity, decimal
RH	Relative humidity, percent
SECO	Specific energy consumption, kJ/kg water
SP	Pressure drop, Pa/m
T	Temperature, °C
t	Time, h
tm	Drying time, minute

W	Water, kg
x	bed depth coordinate, m
Y	Volumetric airflow rate, m^3/min
ϱ	Dry weight density, kg/m^3
θ	Product temperature, °C

<u>Subscripts</u>

$_a$	Air
$_e$	Equilibrium
$_0$	At time t=0
$_p$	Product
$_t$	Time
$_v$	Vapor
$_w$	Water
$_x$	Bed-depth coordinate

1. INTRODUCTION

1.1 Rice Drying in General

Rice grain should be harvested soon after maturing in order to minimize losses due to bird, rodent and insect attacks, due to shattering of overly dry grain, and due to kernel-checking caused by frequent rewetting and drying. The grain harvested at the optimal stage has a moisture content varying from 20 to 24%, wet basis (w.b.). In this dissertation, all moisture values are given on a wet basis (w.b.) unless specifically designated as dry basis (d.b.). The harvested grain deteriorates quickly in the Tropics after about 24 hours of storage. For long-term storage, freshly harvested rice must be dried to a moisture content of 12 to 13.5%. The same moisture content is required for the milling of rice.

This thesis will consider in particular the potential of introducing modern rice drying technology in Malaysia due to the Malaysian background of the author.

1.2 General Methods of Drying Rice

There are numerous methods of drying rice used throughout the world. The object is to rapidly dry the rice at minimum cost while maintaining a high milling yield. During drying, the rough rice is subjected to both temperature and moisture stresses which can cause the formation of checks or cracks in the kernels. The checks are weak points at which the kernel may break during the milling process. Therefore, rice grain with a large number of checks will have a low milling quality. Broken kernels have a much lower price than whole kernels or head rice.

The traditional method of rice drying is sun drying. Harvested rice is spread in a thin 5-10 cm layer over a mat, a concrete floor or the ground and exposed to the sun. Occasionally, the grain is turned to achieve uniform drying. Sun drying is an inexpensive but labor-intensive method of drying rice. However, solar energy cannot be controlled; besides, there is considerable kernel checking. For a large operation, a very large drying yard is needed. For the small rice farmers of Asia, Africa and other regions, sun drying is still very popular for the dry season's harvest.

When sun drying is not possible in the Tropics, mechanical drying is the alternative. Various types of mechanical drying systems are in use. They have the advantage of being less dependent on the weather and of having a faster drying rate. However, they require considerable investment and have high operating costs. All large rice farms and private, public and co-operative rice elevators use mechanical dryers in Malaysia.

Basically, a mechanical dryer consists of a fan or blower, ducting for the air to enter the grain mass, and a structure to hold the grain. Usually, a heater is employed to heat the drying air. A mechanical dryer is normally designed to operate in one of two modes, as a batch system or as a continuous-flow system.

There are numerous variations of the batch drying system. However, the underlying principles are the same. First the drying chamber is filled with grain to the desired level; subsequently all the moist grain is dried to the desired minimum moisture content, is cooled and finally unloaded. The drying chamber holding the grain may be of circular or rectangular design with a perforated floor permitting the drying air to be introduced into the grain. Sometimes, the chamber is a column between two perforated concentric cylinders such that drying air flows in the inner cylinder, flows horizontally through the wall perforations into the grain and exhausts through the outer perforated wall. After a batch is dried and cooled to the desired levels, it is transferred to another bin for storage. Sometimes, the drying bin is also the storage bin.

The continuous-flow drying system offers many variations.

Wet grain is introduced at the top of the drying column and flows through the column by gravity. Drying air is forced through the 0.2-0.3 m grain columns. A metering (unloading) auger removes the dried grain from the dryer at a controlled rate. Wet grain is continually added at the top to maintain a constant level of grain in the grain columns. The drying chamber may be circular or rectangular.

There are three basic high-temperature continuous-flow dryers: (1) crossflow, (2) mixed-flow and (3) concurrentflow. In a crossflow dryer, the drying air flows transverse to the flow of grain (Brooker et al. 1974). In a mixed-flow dryer, the direction of rice flow is diverted by baffles resulting in a mixing action, and the grain is exposed alternately to concurrent and counterflow air. There is a more uniform air exposure and smaller moisture differential of the grain in a mixed-flow than in a crossflow dryer (Bakker-Arkema et al. 1978). In the concurrentflow dryer, air and grain flow in the same direction through the dryer.

The addition of heat to the drying air assists drying by increasing the drying rate of the grain and by reducing the relative humidity of the drying air. In some regions, the relative humidity of the ambient air is low and no heating of the air is required. If dry air is forced through wet grain, considerable moisture can be removed. The mechanical drying with unheated air is not widely practiced in the Tropics because the process is too slow. Furthermore, only a few rice-processing areas in the world have solely a dry climate during the harvest season. Natural air drying has the advantage of not creating thermal stresses in the grain. Thus, the milling quality is maintained.

1.3 Drying Rice in Malaysia

The production of rice has been a major concern in Malaysia since the colonial days in the first half of this century. In 1950, the import of rice in Malaya was 45% of the total requirements. Today, Malaysia is capable of producing 85% of the total annual rice requirement (Fredericks et al. 1983).

Before 1960, Malaysian farmers grew one rice crop per year using traditional varieties, and requiring a long growing season. The yields were lower than those of the new varieties developed in the last decade by the International Rice Research Institute (IRRI) and by local plant breeders. Harvesting used to be carried out only during the dry season. The average rice farmer used to have one to two hectares of paddy; he sun-dried his crop by spreading the wet rice on mats by the road side or in the field. Millers dried rice in drying yards. No government rice elevators existed at that time.

In the sixties, the government started to make large investments in the main rice producing areas in the drainage

Table 1.1 Completed small-scale irrigation schemes in Malaysia, 1981-1983 (Cuddihy 1987).

State	No. of Schemes	Area (ha)	Cropping Intensity (%)		
			1981	1982	1983
Perlis	4	1,278	59	78	107
Perak	3	235	0	9	11
Kedah	23	6,879	40	57	72
Selangor	1	1,000	0	0	0
Negri Sembilan	26	2,776	39	60	68
Malacca	14	1,657	50	30	81
Johor	1	138	29	24	32
Pahang	7	2,559	17	11	9
Trengganu	9	4,322	1	2	2
Kelantan	9	4,489	42	73	69
Sarawak	5	5,863	9	18	24
Sabah	9	4,960	30	38	55
Total	111	36,156	27	38	48

and irrigation systems see Table 1.1. New high-yielding and faster- maturing varieties were introduced. The new varieties were non photoperiodic, and could be grown at anytime of the year. This led to double cropping, the maturing of the second crop during the wet months. Thus, mechanical dryers had to be introduced.

The Malaysian government, anticipating a large increase in the annual rice production, did not expect the private millers to invest in mechanical dryers. In 1971, the government established the national rice board "Lembaga Padi dan Beras Negara" (LPN), to co-ordinate the production, milling and marketing of rice. LPN established several drying centers in the major rice producing areas. Continuous flow dryers of the LSU or mixed-flow design were imported. Each dryer has a capacity of 20 wet tonnes per hour per pass and was supported by 20 aerated tempering bins, each with a capacity of 20 tonnes (Fredericks et al. 1983). In later years, the LPN constructed integrated complexes where rice was dried and milled at the same center. By 1980, LPN had build 28 rice complexes in Malaysia.

Contrary to the government's expectations, the private mills did invest in small batch dryers of 25 to 50 tonnes capacity. These dryers were inexpensive because they were constructed locally, with only the burners and electronic controls bought abroad. The millers claimed that the mobile batch dryers were versatile in drying different varieties, were easy to operate, and were able to produce superior quality dried rice. At present, there are over 300 privately-owned rice mills in the country which own mobile batch dryers; 70% of the total rice crop is dried and milled in these facilities (Muda 1985).

A typical Malaysian farmer sells 70 to 80% of his rice crop to the private or government rice-drying and -milling facilities. He keeps less than one ton a year for household use. This rice is sun-dried and milled at a small cooperative or private mill.

In 1983, Malaysia produced 1.36 million tons of rice. The private mills purchased and dried 70% of the crop using batch and sun drying; LPN purchased 17 to 20% of the crop and dried with continuous-flow dryers; the rest of the crop was sun-dried by farmers and service mills. However, sun-drying is usually not possible during the wet harvest season. Mechanical dryers are heavily relied upon during the rainy harvesting season.

The Malaysian rice industry has definite problems. Hassan and Ranee (1986a and 1986b) reported on the perennial problems of the industry as exemplified during the 1986 wet harvest season when hundreds of paddy-laden trucks formed long queues outside the LPN rice complexes. The average facility can handle about 60 truck-loads or 4000 bags per day with continuous dryer operation. Thus, many trucks had to wait for long periods of time. Some waited as long as two days. A

Table 1.2 Comparison of the qualities of combine-harvested and hand-harvested rice in Malaysia (Rohani et al. 1984).

	Combine-harvested Samples	Hand-harvested Samples
Impurities (%)	5.50	4.20
Injured Grains (%)	0.54	0.00
Cracked Grains (%)	1.60	0.60
Immature Grains (%)	7.40	5.50
Total Milling Yield (%)	66.70	67.30
Head Rice (%)	87.60	92.10
Brokens (%)	12.40	7.90

considerable amount of wet paddy was damaged.

Most farmers prefer to send their wet-season harvests to LPN complexes because the private millers impose heavy deductions on very wet and uncleaned grain. Table 1.2 gives an example of the average quality of rice harvested in Malaysia. While the Malaysian government is helping the poor paddy farmers, it is also trying to reduce LPN's role to solely a regulatory body. Therefore, LPN has not build any new rice-processing complexes. Unfortunately, the private millers are not able to invest in expensive dryers. Under present conditions, they buy wet paddy from the farmers selectively, and buy dried paddy from LPN to run their mills. With the ever increasing rice production in Malaysia, there must be an increase in the drying and storage capacities if losses due to spoilage are to be minimized.

This study analyzes two alternative rice-drying techniques which are at present in use in developed countries. The suitability of each method for the Malaysian conditions will be evaluated technically and economically.

1.4 Objectives of the Study

The main objective of this study is to analyze two major rice-drying techniques for use in Malaysia. The two drying techniques are concurrentflow drying (which is practiced by large grain elevators in the U.S.), and in-bin counterflow drying (which is basically an on-farm method).

The specific objectives are:

(1) To conduct field experiments with the concurrentflow and the in-bin counterflow dryers;

(2) To analyze the capacity and energy efficiency of the concurrentflow and the in-bin counterflow dryers in drying rice in Malaysia;

(3) To make a life-cycle costing analysis of the two dryer types in comparison to custom drying costs in Malaysia.

2. LITERATURE REVIEW

2.1 Causes and Prevention of the Deterioration of Stored Rice

Schroeder and Calderwood (1972) observed that it was man's ability to maintain a constant food supply in a permanent location that allowed him to progress from a pastoral nomad to a modern urban dweller in a technological civilization. The storage of cereal grains has remained the main method of ensuring man a reliable and constant supply of basic foods. Although grain storage has been practiced for thousands of years, annual grain losses in storage remain a major concern. A loss of stored rice of more than 20% is not uncommon in the developing countries of Asia, Africa, and South and Central America. The hot and humid Tropical climate accelerates crop deterioration and promotes the multiplication of macro- and microorganisms that attack the grain. Lack of knowledge and proper application of postharvest technology contribute to the high losses of stored rice in the Tropics.

Rice grain if not properly protected in storage is attacked by birds, mice, and rats. Birds also cause damage by contaminating the stored rice; they can be kept out by covering windows and other openings with hardware cloth.

Cleaning up of spilled rice discourages the birds from feeding in the area. Rats can enter the warehouse through openings in the roof, wall, and floor. Rodents not only feed on the stored rice, but also contaminate the total grain mass; rodent-borne diseases may also be spread. Besides, buildings, machinery, and electrical wiring are damaged from gnawing. Rodents are controlled by using rat poisons or rodenticides. Extreme care must be practiced as these poisons are also dangerous to humans and other animals. Rat traps, placed at the right locations, can also be effective. Gassing or filling the burrows with water may kill or force the rats out of their burrows where they can be killed. Lastly, the building can be ratproofed by preventing the entry of rodents.

Insect pests which attack rice grain in storage include some species of the beetles, the moths, and the weevils. Some begin their attack in the field before harvest and continue in the storage bin. Under favorable conditions, they multiple quickly in the stored rice. Theoretically, it is possible to start with one pair of rice weevil adults and have 6.75 x 10 adults in 6 months (Esmay et al. 1979). The insects can damage stored rice in several ways. They feed and bore holes in the kernels. Rice lots are also contaminated with excrements and dead insects. Live insects respire, giving off heat and water vapor. The water vapor condenses, leading to wet conditions which favor mold growth. Accumulation of heat can lead to hot spots where the grain is discolored and damaged if the heat is intense. In addition, moderate heat in the grain mass stimulates mold growth and insect activity. The insects in stored rice can be controlled by chemical sprays, fumigation or chilling. When rice free of insects is dried and placed in the storage bin, there is little danger of infestation if the grain temperature is low (Brooker et al. 1974). It should be noted that most insects are dormant at temperatures below 10°C. Also, high temperatures above 38°C kill most insects. The optimum condition for growth and multiplication of insects is a temperature of about 20-22°C with sufficient food, oxygen, and moisture. Little insect activity occurs in rice at any temperature if the moisture content is below 10% (wet basis).

Table 2.1 Postharvest rice losses due to insects in Malaysia (cited by Muda 1985).

Storage Method	Storage Period (month)	Estimated Loss (%)	Source
Paddy at Farm in sack or bulk	3 6	6.8 4.8	Rahim et al. 1983
Paddy at Coop. Mill in sack	6 9 12	4.8 3.2 3.0	Rahim 1984
Milled Rice in Commercial Store	unspecified	5-10	Yunus and Singh 1968
Milled Rice in Plastic bag	2-4	7.3-14.2	Rahim and Jamiah 1983

Rodent, bird, and insect damage are sometimes noticeable at an early stage. Appropriate control measures can then be applied. Serious but less conspicuous damage may be caused in the early stages by fungal attack. Christensen and Kaufmann (1969) noted that many warehousemen are unaware of the importance of fungi. Even some trained grain merchants are reluctant to believe that fungi (which they often cannot see) are able to cause severe damages and changes in the stored grain. The inconspicuous nature of the fungi is normal when they invade and decay grain. Only in the final stages of decay can one see the caking of the stored grain and the powdery appearance of the spores, and can one smell the strong musty odor of the molds.

Esmay et al. (1979) listed the damage caused to rice by fungal attack as: 1. the decrease of seed viability, 2. the seed discoloration, 3. the heating and mustiness, 4. the biochemical changes, 5. the production of toxins, and 6. the loss of dry matter. The principal storage fungi consist of several species of the genera Aspergillus and Penicillium, and one species of the genus Sporendonema. The storage fungi are present in spore form in most rice storage areas and hence, stored rice is normally exposed to them.

The storage fungi require favorable conditions to thrive and multiply; the most important are humidity and temperature of the ambient air. Christensen and Kaufmann (1969) explained that even the most drought-resistant storage fungi require for growth a relative humidity of at least approximately 65%. Therefore, grains with moisture contents in equilibrium with relative humidities of less than 65% are safe from fungal attack, regardless of the other conditions of storage. The equivalent safe moisture content is about 13% at a temperature of 30°C. The optimum temperature range for storage fungal growth is between 25 to 30°C (Esmay et al. 1979). As the storage temperature differs from this optimal range, the fungal activity will generally decrease correspondingly. Still some penicillium species grow below 10°C and some aspergillus species develop slowly at temperatures above 35°C (Christensen and Kaufmann 1969).

Brooker et al. (1974) indicated that the condition of the grain at the beginning of the storage period also affects the growth and development of storage fungi. Grain with sound seed coats may be able to keep out the fungi from the starch of the endosperm which is the principal food source for the invading microorganisms. The higher the amount of damaged and broken grain in the store, the more likely fungi will be able to thrive and spread. Christensen and Kaufmann (1969) stated that if the grain has already been invaded by fungi to some extent before storage, it will tend to deteriorate more rapidly in storage when the conditions permit fungal growth, compared to grain that was not infected before storage.

The presence of foreign material is another factor affecting the growth of fungi in stored grain (Christensen and

Kaufmann 1969). Broken grains, weed seeds, plant fragments, parts of dead insects, and soil can accumulate in one section of the bin and fill the inter-spaces between the grains increasing in that section the resistance to airflow. Effective drying or aeration is thus hindered, leading to subsequent deterioration of the grain in that section. Furthermore, the foreign material is an excellent breeding ground for fungi and insects.

Christensen and Kaufmann (1969) discussed the effect of insects and mites on the development of storage fungi. These creatures break down their food into carbon dioxide and water. The accumulation of the water can increase the moisture content of the grain surrounding the insects and mites, thereby accelerating the development of fungi. In addition to providing the suitable conditions for fungal growth, some grain-infesting insects carry inoculum of storage fungi. Thus, an initial problem of insect infestation in a grain store often leads to an additional problem of mold growth. The more visible insects are easily detected and the store may be fumigated to kill them. But, the fungi are not affected, and damage to the grain continues.

Esmay et al. (1979) suggested four methods by which mold growth in stored rice can be minimized. A low storage temperature should be maintained since storage fungi become less active when the temperature falls below 25 C; however, some penicillium species still grow if there is sufficient moisture. Controlling the rice moisture content to below 13% deprive a mold from the humidity needed for growth. The gaseous makeup of the surrounding environment can also be regulated; this can be accomplished by sealing the rice store airtight, thus depleting the oxygen and increasing the carbon dioxide content. The disadvantages of gaseous control are that there is a change in flavor of the rice, and the germs are killed. Minimizing mold growth is also accomplished by treating the rice grain with a chemical such as propionic or acetic acid; fungal growth is stopped but the germs are also killed. While a chemical odor will disappear after some months, the brown embryos have lowered the rice quality to animal feed.

Losses of rice grain in storage are also contributed by the natural process of living. Grain respires and in the process oxidizes dry matter. The process of respiration, in which the hexose sugars of the grain are oxidized to carbon dioxide and water, is described by the following equation:

$$C_6\,H_{12}\,O_6 + 6O_2 \;\dashrightarrow\; 6CO_2 + 6H_2O + 677\text{ Cal} \qquad (2.1)$$

A substantial build up of heat and moisture in the stored rice will damage the rice kernels, and subsequently will promote mold and insect developments. Storage fungi also respire and give off heat at the same time. There is disagreement among researchers which process, fungi or grain respiration, is more

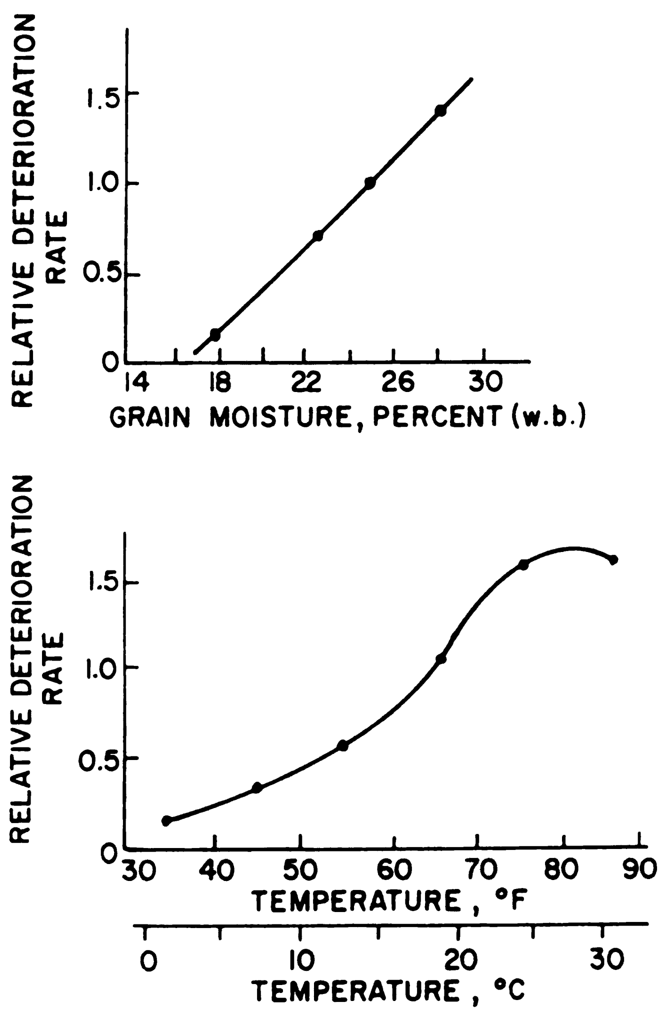


Figure 2.1 The effect of moisture and temperature on the relative grain deterioration rate (Hall 1980).

active and generates the most heat.

Hummel et al. (1954) were able to obtain wheat free of fungi, and measured the respiration over a period of 19 days; they found that the respiratory rate of the mold-free wheat is low and constant with time. Measuring the respiratory rate of moldy wheat, they found that it markedly increased after a few days. They concluded that the respiration of the storage fungi is the major contributor to heat production in stored moist wheat. Thus, maintaining a low grain moisture content will reduce both grain respiration and fungi activity.

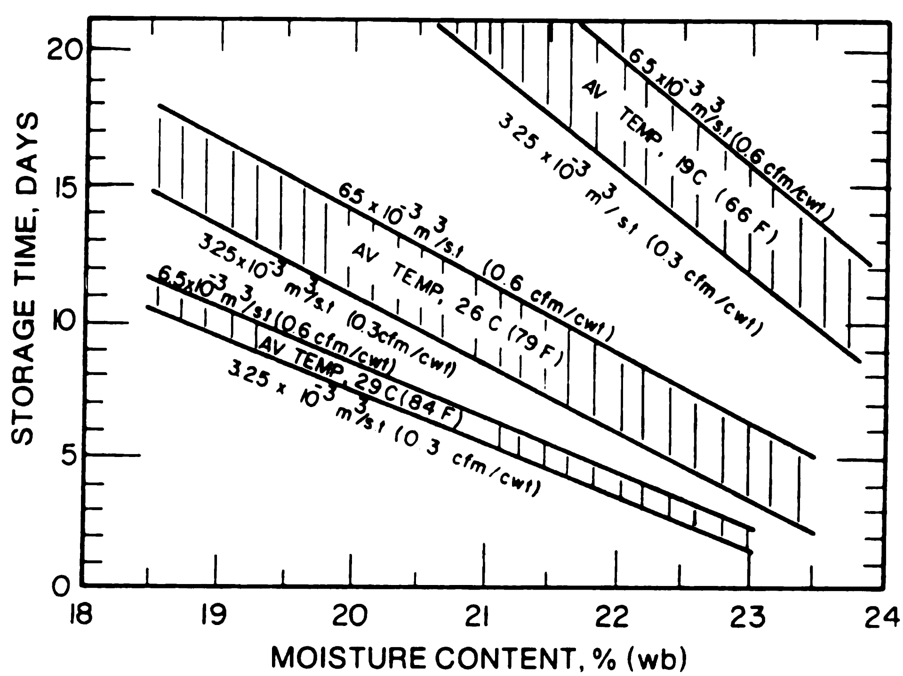


Figure 2.2 Allowable storage duration in aerated bins that will maitain rice quality (Calderwood 1966)

Rice grain that is dried to 13% moisture content or lower, and kept in a storage structure, should be checked for insect activity, mold growth, and grain respiration. Under certain conditions, grain in some parts of the bin or silo can be rewetted by the natural convection movement of air in the storage structure. Brooker et al. (1974) observed that in temperate regions, grain is placed in storage at a relatively high temperature. As the weather turns cooler, the grain temperature close to the wall decreases, increasing the density of the surrounding air. The grain temperature in the center section remains relatively high, and thus the surrounding air is lighter. Therefore, there is a convection current created whereby cool air along the wall moves downward while warmer air in the middle of the grain mass moves upward. The air absorbs moisture from the grain because warmer air has a higher moisture holding capacity. On reaching the top layer, the warm and moist air is cooled because the grain at the top is cooler. Thus, moisture condenses and accumulates at the top of the grain mass. Sometimes, moisture also condenses on the roof of the structure and drips on top of grain. If the accumulated moisture is not removed, spoilage occurs.

During the spring, the opposite situation occurs when the ambient air and the bin wall are at a higher temperature than the grain mass. In this case, air flows down the center of the grain and rises along the walls, condensing moisture at the bottom of the grain mass. According to Esmay et al. (1979), the diurnal air temperature and solar energy changes in the tropics can cause the outer layers of the grain mass to gain or lose heat; this will result in moisture migration. Brooker et al. (1974) suggested that in temperate climates, this problem can be minimized or eliminated by slowly cooling the grain in the fall and warming it in the spring by aeration. This process will reduce the temperature differential across the grain, and thus prevent the occurrence of the convectional current inside the storage structure.

2.2 Optimum Harvest Time for Rice

In the field, rice grain is usually allowed to dry to below 30% before it is harvested. Chau and Kunze (1982) studied the moisture content variation among harvested rice grains of the Brazos variety. They found that optimum head rice yield is obtained when the grain is harvested at moisture contents between 24 and 26%.

Steffe et al. (1980) observed that rice does not mature uniformly. Even on the same panicle, the moisture contents of grains were observed to differ by as much as 5 to 10%. Waiting for all the kernels to mature before harvesting, results in some kernels becoming overripe and susceptible to field cracking. Harvested rice with a high percentage of cracked or checked grains tends to result in correspondingly

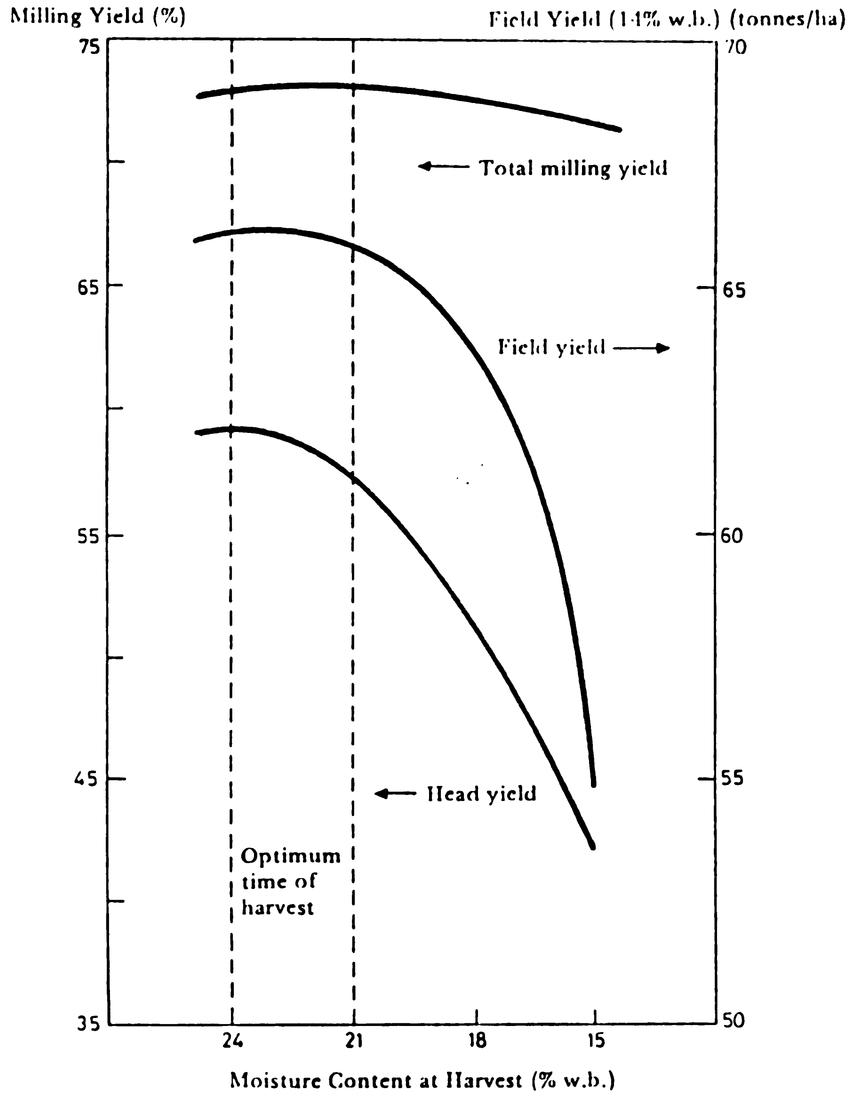


Figure 2.3 Optimum moisture content of rice at harvest time (Bhole 1970).

low head rice yields after subsequent milling. Economically, rice head yield is next only to crop yield in importance. Also, the longer the grain is left in the field, the greater are the chances for attack by birds, rodents, insects, and microorganisms. Thus, the farmer must judge carefully the right time to initiate harvesting in order to obtain the maximum amount of mature grain without sacrificing quality.

Various criteria may be used to estimate the overall maturity of the rice crop and its suitability for harvest. One method recommends harvesting the rice when the kernels in the upper part of the panicles are clear and firm while those at the base are in the hard dough stage (Araullo et al. 1976). The age of the rice crop and the color of the grains can also be used as indicators of maturity. However, the most widely used index to determine crop maturity and proper harvest time is the average moisture content of the rice grain. Esmay et al. (1979) recommended that rice in the tropics should be harvested when the average grain moisture content is about 20%. Slight adjustments to this moisture level should be made according to the variety and the crop handling system. According to Steffe et al. (1980), in California for early maturing medium rice varieties, rice grains in the field with moisture contents below 22% are considered overripe; they should be harvested when the average moisture content is about 24-26%.

McNeal (1950) carried out experiments in Arkansas to determine the optimum time for harvesting rice. He found that for the medium-grain variety Zenith, the highest head yield was obtained from rice harvested at a moisture content between 17 and 23%. Rexark, a long-grain variety, gave the highest head yield when harvested at moisture contents between 16 and 22%.

At the International Rice Research Institute in the Philippines, Khan et al. (1973) investigated four high-yielding long-grain rice varieties, IR-20, IR-24, C4-63G, and IR-253. Their results showed that in general, the head yield and the total rice recovery are maximum when the varieties are harvested at moisture contents close to 20%. Bhole et al. (1970) found in India that the field yield and the total head yield of the popular variety IR-8 are highest when the grain is harvested at a moisture content between 21 and 24%.

2.3 Importance of Drying Rice

Today most rice in the U.S., Africa, and Asia is harvested at a moisture content of 20% or higher in order to obtain the maximum yield with the highest quality. To maintain the quality of the harvested rice during storage, the grain must be dried to about 12-13%. At these low moisture contents, grain deterioration due to the activities of insects, microorganisms, and grain respiration is kept to a minimum. Low grain moisture content is also required during milling. The optimum rice moisture content during milling, resulting in the maximum milling yield and the minimum percentage of broken kernels, is 13 to 14%. Thus, the drying of freshly harvested rice is essential if the rice is to be stored or milled. Furthermore, the drying must be carried out soon after harvesting because high moisture rice begins to deteriorate after about 24 hours (McNeal, 1960).

Other advantages of artificially drying rice are: a) the possibility of storing the dried rice without deterioration, enables the farmer to hold his crop and sell it when prices are high, b) the dried grain is a better-quality product; in the case of seed grain, drying reduces the heating of the grain which destroys or decreases the germination, and hence enhances the viability of the seed, c) artificial drying allows the rice crop to be harvested early when the grain moisture content is still high; this reduces field losses from shattering, bad weather, and attacks by pests, and d) harvest planning and early preparation of land for the next crop are facilitated when the crop is harvested early.

2.4 Rice Breakage

The harvested rice grain is called rough rice or paddy. It consists of the edible kernel protected by the husk or hull (lemma and palea). Paddy is dried to about 13% prior to milling. During milling, the hull is removed by frictional forces of the shelling process to yield brown rice. The germ, the pericarp layer, and the bran layer of the brown rice are removed during the whitening process. The resultant white rice is polished to give the final product a clean, white, and shiny appearance.

Some rice kernels inevitably break during the milling process. Broken kernels which are less than three quarters of their original size are classified as brokens; they are separated into large brokens, screenings, and brewers' rice. The largest broken kernels and the sound kernels are together classified as head rice or whole kernels of the milled rice. Since the market preference for whole kernels is universal, broken milled rice has a lower market value; usually about one half the value of whole rice (Kunze and Calderwood, 1980). Thus, care is taken in all phases of processing to prevent kernel breakage or damage which can lead to breakage during subsequent milling.

Whole and broken rice are the major products of the rice milling process. The milling process is only partially responsible for rice breakage. The rice kernels may have been damaged in the field, during harvesting, handling, drying, or storage. The damage is usually manifested as an increase in broken kernels during milling. After milling, head rice is still susceptible to damage and breakage during subsequent handling and packaging.

Various terms are used by different authors to describe the physical damage of rice kernels. Among them are cracks, surface cracks, sun-cracks, checks, sun-checks, faults, internal faults, splits, fractures, partial fractures, vacuoles, crack rings and fissures (Kunze and Calderwood 1980).

Many studies indicate that a major contributing factor to rice kernel damage is the movement of moisture in the kernel. Kondo and Okamura (1930) carried out studies in Japan to investigate this effect. They air-dried two rice varieties, determined the percentage of cracked grains, exposed the grains to rain for two hours, and again determined the percentage of cracked grains. They found that the rewetting of the dried rice grain caused considerable cracking of the kernels. For the Kibiho variety, the increase in the amount of cracking was 0.0 to 34.3% and for the Asahishinriki 1.7 to 11.3%. In another experiment, they found that the longer the paddy was exposed to rain, the greater the percentage of cracked grain; the extent of cracking tended to develop progressively with time. It was also concluded that varietal difference affects the susceptibility to cracking, and that milled rice is more susceptible than paddy.

Stahel (1935) coined the terms sun-checking and sun-cracking, implying the sun is responsible for causing the cracks in kernels, while the grain dries in the sun. However, sun-checking/cracking is a misnomer. High moisture paddy can be dried in a thin layer in the sun to below 10% moisture without checking; however, fissures develop if the rice is allowed to readsorb moisture.

Stermer (1968) studied the effect of environmental conditions on stress cracks in milled rice. He observed that there are two kinds of kernel damage. One is due to moisture desorption (drying) and the other due to moisture adsorption (wetting). Cracks formed by moisture desorption are irregular whereas those by adsorption are straight. Damage due to moisture adsorption was thought to be more serious because cracks due to desorption sometimes disappear. However, both types of damage cause the kernel to be easily shattered in mechanical breakage tests.

Kunze and Hall (1965 and 1967) placed brown rice in environments of increasing relative humidity. By increasing the relative humidity by 10% in 24 hours, no fissures developed. Fissures did develop when the difference between the higher and lower relative humidities was increased by 20% or higher.

Kunze and Calderwood (1980) designated the moisture content to which rice must be dried before it fissures due to rapid adsorption of moisture, as the critical moisture content. According to these researchers, the critical moisture ranges between 14 and 26%; rice grains at higher moisture content is sufficiently plastic to resist fissuring. Varieties and environmental conditions are thought to influence the threshold moisture.

Chau and Kunze (1982) found that at harvest time,the moisture content difference between grains on a panicle for the driest panicles is less than 10%, while for the wettest panicles, the difference in moisture content is well above 10%. Also, measurements made 6 days after the date of normal harvesting showed that the difference in moisture content between grains from the top of the driest panicles and those from the bottom of the wettest panicles can be 46%. With an average grain moisture content of 24 to 26%, part of the crop has a moisture content close to the critical moisture content. Some grains will have dried to below the critical moisture content and will have redesorbed moisture several times before being harvested. Therefore, under normal conditions, it is likely that kernel fissuring starts in the field. The extent of the problem depends on the variety and the weather conditions.

Harvested rice of varying moisture contents is mixed in combine harvesters, transport bins, conveyors, holding bins, and dryers. Using the table on "Hygroscopic Equilibria of Rough Rice" by Wratten and Kendrick (1970), Kunze and Calderwood (1980) explained that rough rice at a moisture content of 22% and a temperature of 26.7°C produces an intersticial relative humidity of 97%, while rice at the same temperature but at 14% moisture content exhibits an interstice relative humidity of 75.6%. Under these conditions the low moisture rice absorbs moisture and may fissure.

Calderwood (1984) studied the milling yield of rough rice blended at different moisture contents. He found that when equal amounts of rough rice within the range of 12 to 22% moisture content are mixed, moisture adsorption has little or no effect on whole kernel head yields. However, when overdried rice at a moisture content of 8% or lower is mixed with rice at a moisture content of 17% and higher, there is a severe reduction in head yield. He concluded that variety might effect the tolerance to mixing so that varieties which characteristically produce high head yields have a higher tolerance to mixing over a wide range of moisture contents.

Another important cause of rice grain damage is combine harvesting. Matthews and Spadaro (1975) collected rough rice harvested by combines with normal operation settings from fields of five farmers. They also harvested samples by hand from the five fields. Upon examination by X-Ray photographs, they found that the combine-harvested samples averaged 6.1% broken and cracked grains while the hand-harvested samples averaged only 0.4% broken and cracked grains. After milling, the combined-harvested rice had an average of 11.2% broken kernels and the hand-harvested samples only 6.0%. Clearly, the combine harvesters, contribute substantially to rice kernel damage, and subsequently to lower head yields.

Rice cracking or fissuring during and after drying is an important criterion in deciding the effectiveness and success of a rice-drying technique. Many researchers have carried out studies to determine the causes of rice fissuring associated with drying. Basically, the main generators of the fissures and checks are two modes of moisture movement in the kernel, desorption and adsorption.

Ban (1971) studied rice cracking at high drying rates. He found that in drying rice from 20 to 13.5%, a maximum drying rate of 1.5% moisture removal per hour can be used without affecting head yield. Higher drying rates can be used but drying at those rates must stop when the grain moisture content reaches 17 to 18%. Ban (1971) also studied rice cracking during rapid drying by placing the rapidly dried rice in airtight containers so that neither desorption nor adsorption occurred. He found that the rice grains do not necessarily crack during or immediately after drying; cracking begins several hours after drying, and can continue for about 48 hours.

Kunze (1979) explained that in the case of the rapidly dried grain, a moisture gradient is created in the kernel. After drying, the moisture gradient declines with time as moisture from the interior diffuses to the outer surfaces. This causes the outer portion of the kernel to expand and develop compressive stresses while the interior contracts and develops tensile stresses. When the stresses are greater than the tensile strength of the interior, the kernel cracks.

Kunze and Prasad (1978) simulated the drying conditions in a dryer; high and low moisture rice were mixed and dried

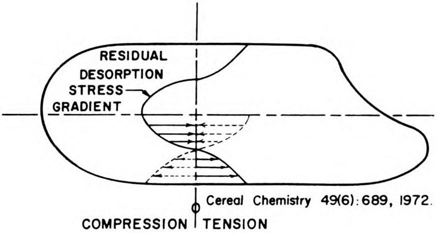


Figure 2.4 Hypothetical stress distribution within the rice kernel (Kunze and choudhury 1972).

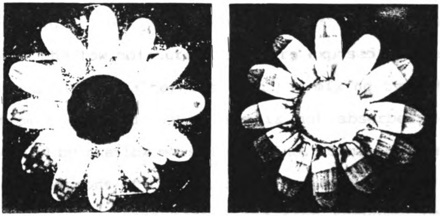


Figure 2.5 Cracking patterns; left- rapidly dried milled rice, right- rapid moisture adsorption in brown rice (Kunze and Choudhury 1972).

together. They placed low moisture (10-12%) brown and rough rice in screen envelopes on top of a drying column of high moisture rough rice. Air at 60°C was blown through the drying column. Initially, the exhaust air was at 100% relative humidity; as the drying progressed, the exhaust air became less humid. Drying was stopped when the exhaust air reached 37.8°C. The results show that when rough rice at a moisture content of 20.5% and higher is dried in the column, more than 80% of the low moisture rice fissures. The authors concluded that during artificial drying of rice, the heated air after passing the drying front, becomes humid. Low moisture rice ahead of this front absorbs moisture from the humid air and may fissure.

Kunze and Prasad (1978) inferred that a mixing type dryer will produce higher head yields than a non-mixing column type dryer because the low moisture grains are exposed to the hot-dry and warm-humid air alternately in the mixing type dryer. Moisture from the humid drying air is not absorbed for an extended period by the low moisture grains. Similar reasoning can be used in support of the multipass drying technique where rice is dried for a short period and then tempered between passes. Again, the low moisture rice is exposed to the humid air for only a short duration, limiting adsorption of moisture by the kernels. Additional passes of short duration minimize the tendency for the rice kernels to fissure.

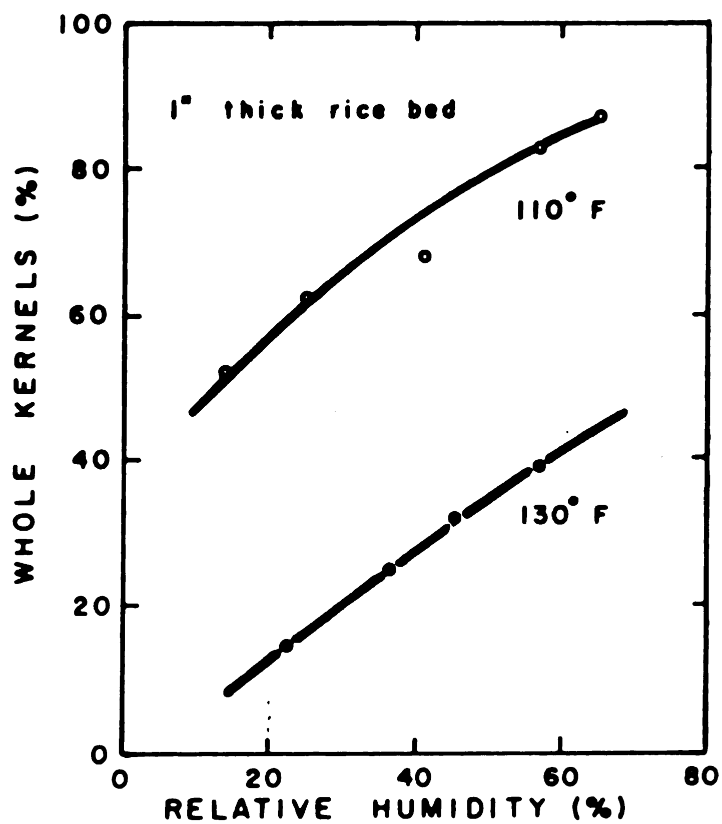


Figure 2.6 Effect of drying-air temperature and relative humidity on rice head yield (Henderson 1957).

Tempering during the rice drying process refers to the holding of rice between drying passes. During tempering, moisture migrates from the kernel interior to the outer surfaces, equalizing the moisture content throughout the kernels. In practice, the duration of the tempering periods varies between a few hours to 24 hours or more. Beeny and Ngin (1970) found that a short tempering period (10 minutes) leads to low head yields. A dramatic increase in head yield is observed when tempering time is increased to 5 hours. Increasing tempering time further to 10 hours does not markedly improve head yield.

Wratten (1959) observed that there is an increase in drying efficiency with tempering up to 24 hours. The drying efficiency referred to here, is the drying capacity in terms of moisture removed per unit time of dryer operation. The greatest increase in efficiency occurs during the first 6 hours of tempering. During the last 12 hours of tempering, the drying efficiency increases slowly. Steffe and Singh (1980) found that for a temperature of 35°C, tempering is 95% complete in less than 2 hours, and fully complete in less than 5 hours. Maintaining higher temperatures during tempering reduces the required tempering time. However, rice should not be tempered at temperatures, at 40°C or above for more than 24 hours as damage due to yellowing might occur (Kunze and Calderwood 1980).

After the rice is dried to the required storage moisture content, subsequent damage to the kernel is greatly affected by the storage conditions. Sharma and Kunze (1982) studied the development of fissures in rough rice after drying. They found that rough rice at field or storage moisture dried at 60°C for 2 hours or more, fissures shortly after drying while only a few kernels fissure during drying. Rapidly drying rough rice from field to storage moisture contents in one pass at 60°C results in many kernels fissuring within 48 hours after drying with additional fissures developing slowly during the next 72 hours. High moisture rough rice fissures more than low moisture rice when subjected to a high drying potential for 2 hours or more. Since kernel fissuring commences after drying, Sharma and Kunze (1982) feel that rice can be dried rapidly, and subsequent fissure development can be prevented by introducing a suitable post-drying treatment.

Kato and Yamashita (1979) studied methods for preventing rice cracking. They rapidly dried rough rice, 2.5 to 6.0% moisture removal per hour, and stored it in sealed containers at temperatures of 0, 20, 40, 50 and 60°C. They found that the percentage of fissured grains is reduced at high storage temperatures.

Nguyen and Kunze (1984) investigated the development of rice fissures in relation to post-drying treatment. Two rice varieties, long-grain Labelle and medium-grain Brazos, were used. After drying, the grains were stored in sealed containers under various temperature and humidity combinations; the temperatures were 10 and 45°C while the relative humidities were 11%, 43% and 75%. Two air drying temperatures were used: 40°C and 60°C. The results show that higher air drying temperatures produce considerably more fissures for both varieties. Also, in all cases, the storage of dried rice at lower relative humidities minimizes fissure development. For the Brazos variety, storage at 45°C produces less fissuring compared to storage at 10°C. The storage temperature effects on the Labelle variety were inconsistent.

In summary, it is important to note that there are numerous causes of rice breakage, from the choice of variety in the production stage to the final storage conditions of milled rice prior to consumption. The best drying technique cannot guarantee the highest quality milled rice, but a poor one will result in a low head yield.

In theory, it is possible to dry rice rapidly and then apply a post-drying treatment to prevent grain fissures (Sharma and Kunze 1982). However, no practical method has been found. In order to minimize rice breakage due to drying, rice is still dried relatively slowly at low temperatures. For the nonmixing-type dryers, the air temperatures seldom exceed 54°C while air temperatures as high as 66°C are used in mixing-type dryers (Kunze and Calderwood, 1980). High moisture gradients in rice kernels are avoided by drying in multipasses or multistages. During each pass, the moisture content is reduced by 2 to 3% of the dry weight, and there is a tempering period of 4 to 24 hours between passes to equalize the moisture concentration (Kunze and Calderwood 1980). The challenge to the dryer operator is, therefore, to dry rice as efficiently as possible under these constraints.

2.5 Drying Principles

2.5.1 Moisture Transfer

Moist air contains water vapor mixed with the other gases, nitrogen, oxygen, argon, carbon dioxide, neon, etc. The water vapor molecules present in the air exert a partial pressure, referred to as vapor pressure. For a given barometric pressure, the vapor pressure is dependent on the temperature and the amount of water vapor in the air which is usually expressed as the relative humidity or the humidity ratio. Rice grains containing moisture also exhibit a characteristic vapor pressure at a certain temperature and moisture content.

When the air surrounding the grain has a lower vapor pressure than the surface of the grain, moisture moves from the grain to the air. Conversely, the hygroscopic rice grain adsorbs moisture from the environment when the vapor pressure of the environment is greater. Adsorption and desorption of moisture between the grain and the air ultimately equalize the vapor pressures. At that point, the grain is said to have reached its equilibrium moisture content (EMC), and the environment is said to be at the equilibrium relative humidity.

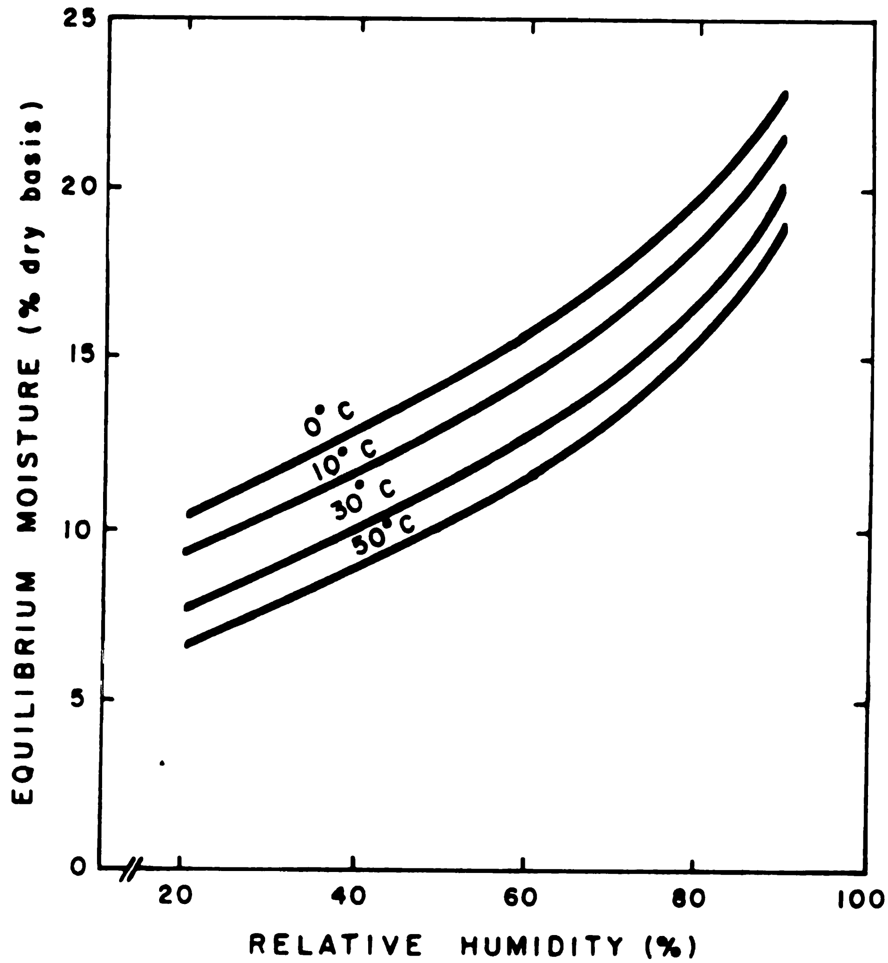


Figure 2.7 Equilibrium moisture content of rough rice (Pfost et al. 1976).

By definition, the EMC of a cereal grain is the final moisture content the grain displays after it has been exposed to a given environment for an infinitely long time. The EMC of the grain is important because it determines the minimum moisture content to which the grain may be dried for a given drying condition. Factors which determine the EMC of a cereal grain are the species, variety and maturity of the grain, the grain "history", and the temperature and humidity of the surrounding air.

Drying is a process of heat and mass (moisture) transfer. During air drying, air flows by natural convection over the rice grain, spread on a drying floor, or the air is forced by forced convection through the rice bed in a dryer. In the case of heated air drying, the air carries energy into the system to evaporate the grain moisture. The moving air also carries the evaporated moisture away from the system. During the cooling, ambient air is blown through the grain mass to cool the grain. Depending on the condition of the air, moisture may or may not be absorbed by the grain during cooling. In sun drying, energy for evaporation is absorbed by the grain from direct solar radiation. Some heat is transferred from the drying floor.

In order to increase the rate of drying, the difference in vapor pressures between the grain and the surrounding air must be increased. Passing heated air through the grain mass will result in energy being transferred to the grain. The vapor pressure of the grain is increased. The heating of the air, also decreases its relative humidity. The vapor pressure difference is not effected by an increase in the air temperature alone. With heated air drying, the drying rate is accelerated only when the vapor pressure of the grain is increased.

Lowering of the vapor pressure of the drying air can be accomplished with calcium chloride and silica gel; both absorbants have been used to remove moisture from the drying air to lower the vapor pressure. Moisture is exhausted in vacuum dryers to maintain reduced vapor pressures. Cold surfaces can also be employed to keep vapor pressures low.

The vapor pressure theory explains the drying of individual particles. In order to understand more explicitly what happens during the actual drying of rice or any other grain, attention should be focussed on both the drying of individual kernels and the drying of a bed of kernels.

2.5.2 Drying of Individual Rice Kernels

Theoretically, the drying of cereal grains can be divided into two stages, the constant rate and the falling rate periods. Very high moisture grain, containing free water on the outer surfaces, will dry at a constant rate when exposed to constant environmental conditions because the resistance to moisture movement in the kernel's interior is less than at the

A-B heating or cooling period
B-C constant rate drying period
C critical moisture content
C-D first falling rate period
D-E second falling rate period

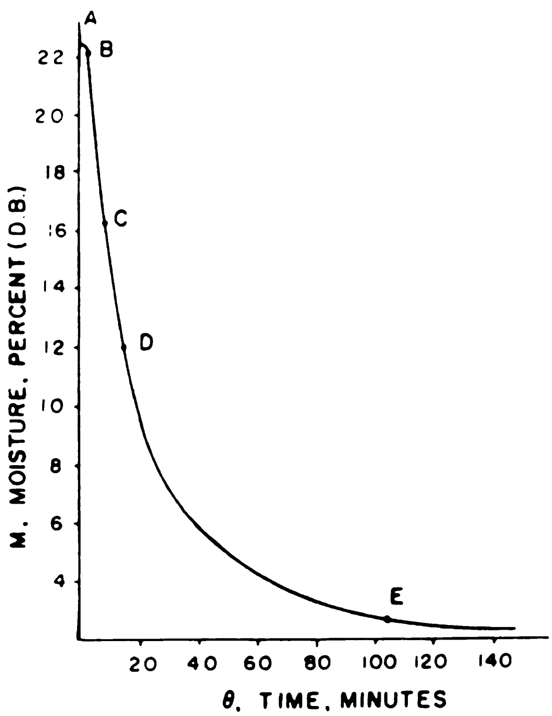


Figure 2.8 Drying rate curve (Hall 1980)

surface. During this drying phase, the rate of drying is affected only by the environmental conditions such as the humidity, the temperature and the velocity of the air.
In practice, only agricultural products with very high moisture contents such as fruits and vegetables will initially dry at a constant rate. Rice grains that are immature or have been soaked by rain, flood, or parboiling practice will sometimes dry at the constant rate period.

Rice is usually harvested below 30% moisture content. The drying of most cereal grains occurs at initial moisture contents no higher that 35% (w.b.) and final moisture contents no lower than 10% (w.b.) (Hukill, 1955). In this moisture content range, the individual kernels do not contain free water. Thus, the internal resistance to moisture movement is greater than the external resistance. As the grain dries, its vapor pressure decreases and hence the drying potential (vapor pressure of grain - vapor pressure of air) is reduced. Therefore, as drying progresses, the drying rate falls. Cereal grains usually dry entirely within the falling rate period.

As moisture is removed from the grain's surface during drying, a moisture gradient is created within the kernel. Equilibrating forces force moisture from the wet center to the dryer surface. The internal moisture movement in the kernel limits the rate of drying during the falling rate period.

Various physical mechanisms have been proposed to describe the movement of moisture inside porous products such as cereal grains (Bakker-Arkema et al., 1978). They are:

(1) liquid movement due to surface forces (capillary flow);
(2) liquid movement due to moisture concentration (liquid diffusion);
(3) liquid movement due to diffusion of moisture on the pore surfaces (surface diffusion);
(4) vapor movement due to moisture concentration differences (vapor diffusion);
(5) vapor movement due to temperature differences (thermal diffusion);
(6) water and vapor movement due to total pressure differences (hydrodynamic flow).

2.5.3 Drying of Rice Kernels in Bulk

In practice, grains are dried in bulk. Ambient air passes over a thin layer of rice, spread over a large drying floor, in the case of sun drying. Air is forced through thicker beds of rice in conventional mechanical dryers. For the drying of single kernels, the heat and mass transfer analysis is facilitated by assuming the air to be at constant conditions and flowing at a constant rate. The same assumptions cannot be made for the drying of grain in bulk. While the inlet air can be kept fairly constant, its characteristics change after contacting the first layer of grain, and will continue to change after subsequent layers. Thus, each layer of grain in a drying bed is exposed to drying air at different conditions.

The characteristics of deep-bed drying can be illustrated by examining the drying of rice in the common farm-bin dryer. Rice is filled into a cylindrical steel bin with a perforated floor, several feet deep. Underneath the floor is the plenum chamber. Heated air passes upwards through the perforated floor and the rice bed, and exhausts through the top of the bed.

When the drying air contacts the first layer of rice immediately above the perforated floor, moisture is transferred from the grain to the air. The humidity of the air is increased, increasing its vapor pressure and decreasing its drying potential. As the air moves further upward through the bed, its humidity is further increased. The grain nearest the plenum, therefore, meets the driest air while those in layers away from the plenum meet air with increasing humidity. Drying will proceed upwards through the bed at a decreasing rate until the air is saturated or reaches the equilibrium relative humidity. No further drying occurs as the moist air moves upward and exits the grain mass at the top of the bin. Drying takes place in the beginning, only in a narrow zone above the drying floor. The narrow layer is commonly called the drying zone. This narrow layer dries close to completion before other layers are substantially affected (Hukill 1947). As the bottom layer approaches the equilibrium moisture content, the drying zone moves upward. Thus, drying proceeds layer by layer until the drying zone reaches the top of the bed.

The thickness of the drying zone depends on the moisture content, temperature and drying characteristics of the grain, and the temperature, humidity and flow rate of the air. If conditions such as a relatively shallow grain bed, low grain moisture content, and high airflow rate exists, the whole bed will start drying at the same time. The drying zone then encompasses the total thickness of the bed. However, the drying rate will still be fastest close to the plenum chamber, and slowest close to the top of the bed.

In drying a deep bed of grain with heated air, condensation can occur when warm/humid air from the drying zone passes through cooler layer of grain in the top of the bin. This so-called "sweating" occurs especially in the early stages of drying when the upper layers of the grain bed have not warmed up to the drying air temperatures. Sometimes, condensation occurs only at the upper surface where heat is lost by radiation. There is no serious waste of fuel as heat of vaporization is transferred to the grain upon condensation. However, molds might develop if the wet conditions persist. Increasing the airflow rate can alleviate the problem.

Another important feature of deep-bed drying is the tendency for the rice closest to the plenum to be overdried. Overdrying of rice grain causes unnecessary loss in weight, wastage of fuel, and more importantly, loss in head yield. In order to have a more uniform drying, the bed has to be shallow. But, with a shallow bed, the drying air will exhaust from the dryer before reaching the equilibrium relative humidity. This will reduce the energy efficiency. Thus, there is a trade-off between fuel economy and uniformity of the final grain moisture (Hukill 1955).

2.6 Mechanical Drying Systems

There are several types of mechanical dryers used to dry rice. No dryer is superior to another in all aspects. Usually, for a specific drying task, there will be several dryers that can be chosen. Two types of mechanical dryers suitable for drying rice on the commercial scale in Malaysia are compared in this study. They are the in-bin counterflow, and the concurrentflow dryers. Their features and characteristics will be described in the following sections. Also discussed is the mixed-flow dryer because it is at present in limited use in Malaysia.

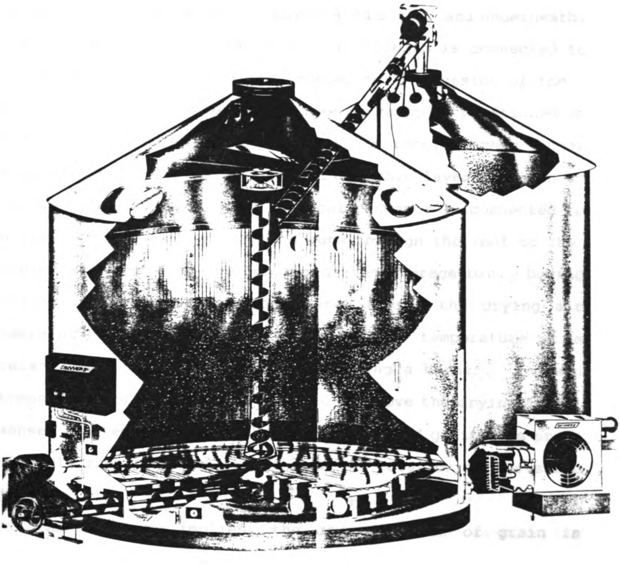


Figure 2.9 The Shivvers in-bin counterflow dryer.

2.6.1 In-bin Counterflow Dryers

The in-bin counterflow dryer is basically a fixed-bed cylindrical bin dryer with a perforated floor, and underneath, the plenum chamber (Figure 2.9). The plenum is connected to the heater and fan which are located on the outside of the bin. In addition, a vertical screw conveyor is positioned in the center of the drying chamber. A tapered sweep auger rotates around the bin, transporting a thin layer of grain to the vertical conveyor. The vertical conveyor is connected to a slanting screw conveyor which runs through the roof to the top of a second bin, the cooling or the storage bin. During drying, a thermostat in the plenum senses the drying air temperature and maintains the drying air temperature at a relatively constant level by controlling a burner. A grain temperature probe, located about 20 cm above the drying floor, senses the temperature of the partially dried grain; the probe controls the start and stopping of the rotation of the sweep auger.

As the name implies, the downward flow of grain is opposite to the upward flow of air. The flow of air is continuous, the flow of grain is intermittent. Usually, the dryer is filled to a certain depth before the fan and the burner are started. Drying proceeds in the same manner as in a fixed-bed or batch system. The bed of grain dries in layers with the layer closest to the plenum drying first.

As the grain dries, its temperature increases because less heat is dissipated through evaporation. When the grain temperature probe senses that the temperature for the driest layer has risen to a preset value, it activates the sweep auger. The sweep auger makes one revolution around the bin, starting and ending under the temperature probe, removing a 7.5-11 cm layer of dried grain to the center auger which conveys the warm partially dried grain to the cooling bin. As this layer is removed from the bin, the cooler, higher moisture grain layers move down causing the probe to register a lower temperature and deactivating the sweep auger. The cycle is repeated when the new bottom layer reaches the preset temperature. New batches of wet grain may be added to the bin as the layers of dried grain are removed at the bottom, making this in-bin counterflow dryer a continuous drying system.

Activation and deactivation of the sweep auger is controlled by the temperature probe; the grain temperature is used as an indication of the desired final moisture content. Shivvers Inc. introduced a computerized dryer controller, the "COMP-U-DRY" (Shivvers Inc. 1985). This unit samples the grain being transferred, and determines its temperature and moisture content. Based on the moisture measurements, the computer will stop or allow the sweep auger to continue to run. If the moisture content is higher than the preset value, the sweep auger is stopped and the computer estimates the additional drying time needed. The "COMP-U-DRY" system was tested in the study.

Bakker-Arkema et al. (1980) and Kalchik et al. (1981) tested and compared on-farm grain drying systems. They found that the energy efficiency of drying corn with the in-bin counterflow dryer increases from 5,110 kJ/kg of water to 4,390 kJ/kg of water when the drying air temperature is increased from 50 to 93°C. The corn quality is not seriously affected by the high temperatures. Silva (1980) compared five corn-drying systems and found that the operating cost per ton of drying corn with the in-bin counterflow dryer is lower than with batch drying, natural air drying, and low temperature drying. In-bin dryeration had the lowest cost for drying a ton of corn.

The Midwest Plan Service (1988) recommended a range of 0.9 to 2.75 m as optimum bed depths for drying grain in the in-bin counterflow dryer. However, Marks et al. (1988) through simulation, found that for minimum energy consumption while maintaining maximum drying capacity, the optimal bed depth is 1.8 m when the dryer is operated with one filling of wet corn and no refilling. The above authors also determined that when operating the in-bin counterflow dryer as a continuous system by periodically refilling wet corn at the top, maintaining a steady operating bed depth of 1.4 m is optimum.

There is no research reported in the literature on the in-bin counterflow drying of rice.

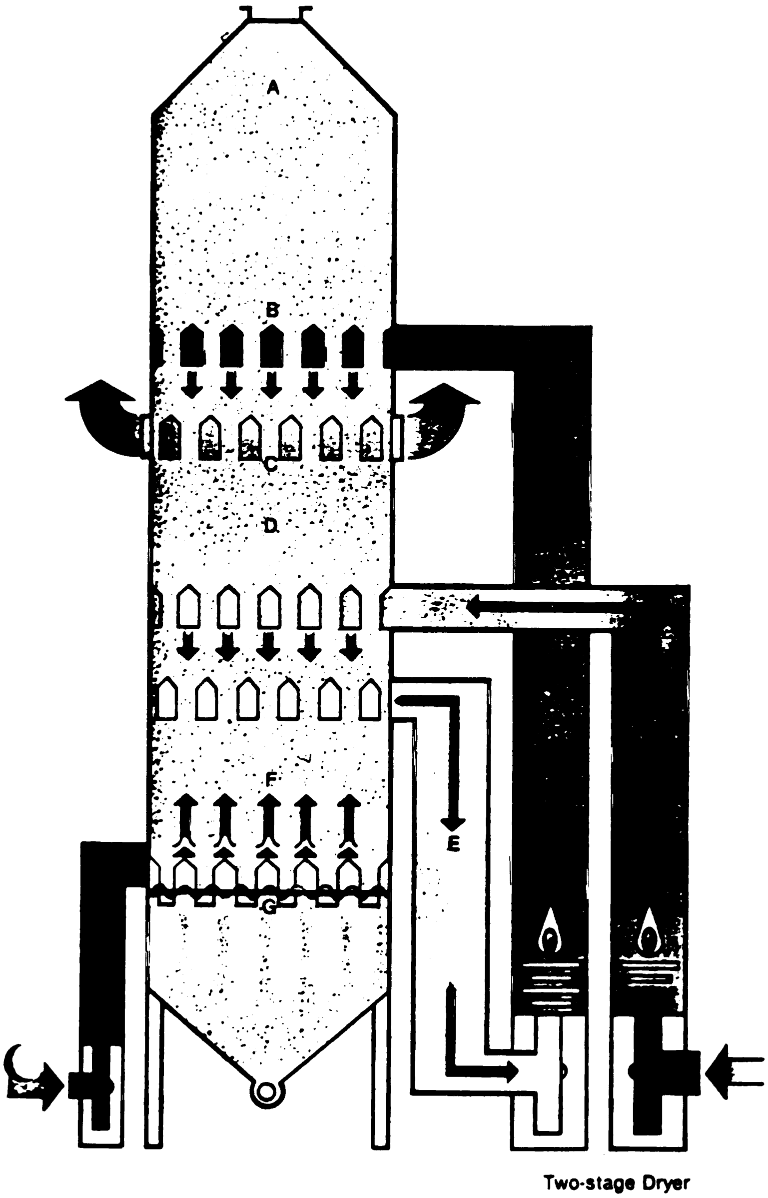


Figure 2.10 The Blount two-stage concurrentflow dryer.

2.6.2 Concurrentflow Dryers

A concurrentflow dryer is a continuous-flow device. The grain enters the dryer at the top and flows down by gravity; the rate of flow is controlled by the unloading auger located at the bottom of the dryer (Figure 2.10). Heated air is blown in the same direction as the flow of grain, and is exhausted through a series of ducts at the bottom of the drying bed. The depth of the drying bed is between 0.75 to 1.50 m. The heated and dried grain is cooled countercurrently, in a cooler located below the drying sections. The air and grain flow in opposite directions in the cooler. Such a dryer is called a one-stage concurrentflow dryer with a counterflow cooler. There are designs such as a two-stage or a three-stage concurrentflow dryer. In a three-stage concurrentflow dryer, there are three drying beds and two tempering sections. A two-stage dryer has two drying stages and one tempering zone. All concurrentflow dryers have one counterflow cooling section.

As the wet grain flows down in the garner bin, it is preheated to some extent. In the drying bed the heated air and the grain flow in the same direction causing the hottest air to contact the wettest grain. The temperature of the air quickly falls while that of the grain rises slowly because of the high rate of evaporation. The cooler air flows through the drier grain to the exhaust ducts. Concurrentflow drying avoids severe heat stresses in the grain even though high drying air temperatures are used.

In a multiple-stage dryer, there is a tempering (steeping) zone between subsequent drying beds. While in the tempering zone, the grain is isolated from the ambient and the drying air, allowing moisture and temperature gradients in the kernel to equilibrate. The duration of tempering depends on the length of the tempering zone and the grain flow rate. In the multiple-stage dryers, the drying air temperature is highest in the top stage and is decreased in subsequent stages to correspond with the reduced moisture contents of the grain and prevent undue stresses. After the final drying stage, the grain is cooled in the counterflow cooler.

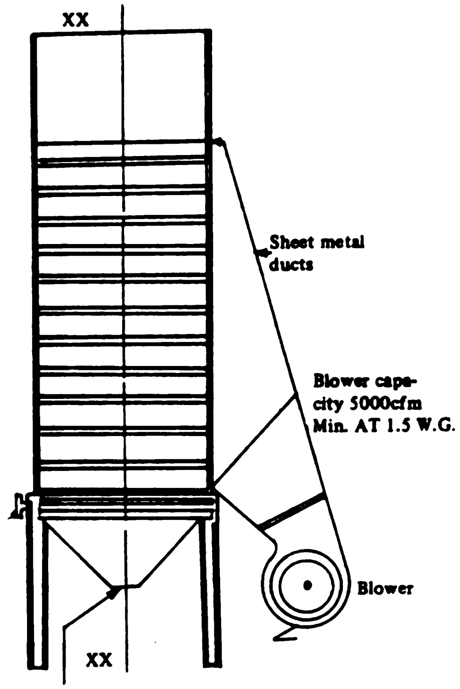
In a counterflow cooler, the rice is again mildly treated because the cool unheated air first meets the coldest grain and then the warmer grain when the air temperature has increased. At the end of the cooling treatment, the grain is conveyed to a temporary holding bin while waiting for another drying pass or to the final storage bin, depending on the moisture content attained.

The ability of the concurrentflow dryer to use higher temperatures for drying and yet avoid excessive thermal and moisture stresses, makes it very attractive for the high capacity drying of rice. Bakker-Arkema et al. (1982) tested a two-stage and a three stage concurrentflow dryers for drying long-grain and medium-grain rice. They concluded that the energy efficiency of the two dryers is between 3500 - 3600 kJ/kg which is about fifty percent below the usual energy required by conventional high-temperature rice dryers. The currently used commercial crossflow and mixed-flow dryers use temperatures ranging from 43 to 66°C and remove 2 to 3 points of moisture per pass when drying rice. The concurrentflow dryer employs temperatures between 120 and 177°C, removes at least 6 points of moisture without affecting the head yield (Fontana 1983).

2.6.3 Mixed-flow Dryers

The mixed-flow dryer, also known as the cascade dryer or the LSU dryer (because of early developmental work at Louisiana State University), is a continuous dryer that is popular with rice producers in Asia. Bakker-Arkema (1984) described the dryer's operation as a combination of crossflow, concurrentflow and counterflow. Grain flows down by gravity through a chamber, installed with rows of inverted V-shaped lateral air ducts across the chamber (Figure 2.3). Each duct is opened at the bottom and closed at the top. The rows are arranged such that alternate rows (inlet ducts) are opened to the heated air plenum and to the exhaust. Often, the arrangement of the ducts in subsequent rows is staggered so that the grain zig-zags through the drying chamber.

During drying, wet grain is filled from the top and it



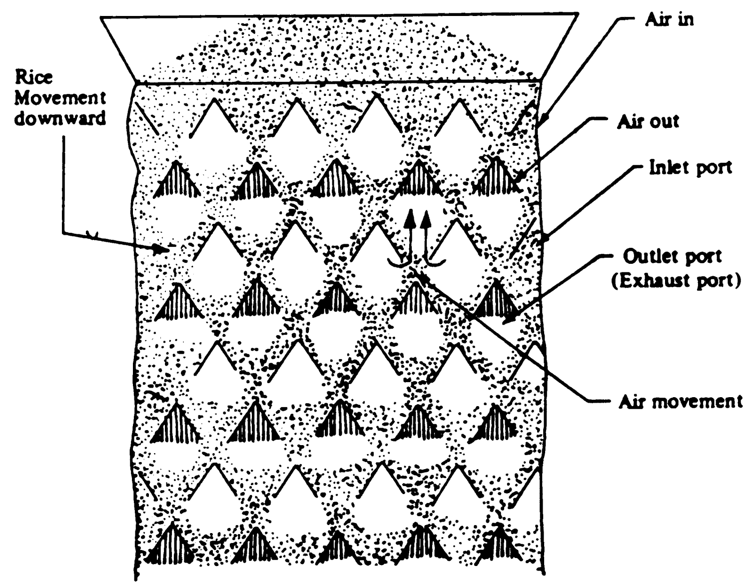


Figure 2.11 The LSU mixed-flow dryer.

flows down by gravity over the inlet and exhaust ducts. The rate of flow is controlled by the discharge augers located at the bottom of the dryer. Heated air from the plenum is blown into the inlet ducts, passes through the grain and into the exhaust ducts. The flow pattern of the grain down the drying chamber results in the grain being thoroughly mixed. Thus, no grain is over-exposed to the hot inlet air or, in the cooler, to the cool, moist air. The design allows the use of relatively high inlet air temperatures. As much as 40% less air and energy is needed for mixed-flow dryers compared to crossflow dryers of similar size (Nellist (1982). Ohja (1974) suggested a temperature range of 60 to 70°C and an airflow rate of 70 m^3/min/ton may be used when drying rice.

Araullo et al. (1976) stated that in the mixing-type dryers, chaff and other light materials are blown out with the exhaust air, decreasing the foreign material in the rice. However, this will lead to dusty exhaust air which may be prohibited by some laws. In the U.S., expensive air pollution equipment is required with this dryer, making it less popular in the last ten years (Fontana 1983).

2.7 Simulation of Grain Dryers

The simulation (or modeling) of a dryer is the representation of the dryer by mathematical equations of which the solution predicts the behavior of the equipment.

Based on theory, experiment or both, differential equations are mostly employed to describe the characteristics of the drying process. Usually, it is impossible to find analytical solutions to these equations. So numerical methods have to be used, and the computer is essential to speed up the involved computations.

The solutions obtained have to be verified by checking the output data against experimental data. If the experimental and the simulated values match within acceptable limits, the model is considered to satisfactorily predict the behavior of the dryer. Further investigations into dryer characteristics and drying parameters can be carried out in a sensitivity study with the model on the computer. This is much faster, more convenient, and less expensive than testing the real dryer. Another important feature is that almost an unlimited number of drying parameters and dryer designs can be experimented on the computer which will be impossible to do in the laboratory.

In order to model the process of drying a particular grain, the drying behavior of the individual grain kernel and the bed of the grain must be known and mathematically represented.

2.7.1 Single Kernel Drying Equations

The equations describing the drying of a single kernel are often called thin-layer equations, referring to the drying of a layer of grain, one kernel thick. These equations predict the rate of drying of single kernels under known drying conditions.

Basically, thin-layer equations can be classified into three groups. One group consists of theoretical equations. Equations based on the diffusion theory have been developed that try to mathematically describe moisture movement in the kernel by diffusion. The simplification of the diffusion equations results in the semi-theoretical drying equations (Brooker et al. 1974). The semi-theoretical equations belong to the second group. The more useful group of drying equations are the empirical drying equations. The empirical equations are developed by the statistical analysis of data obtained from drying thin layers of grain. They are often more accurate at predicting the drying behavior of single kernels. The Michigan State University drying models usually employ empirical thin layer equations.

Empirical thin layer equations are able to predict accurately the drying rates of grains over specific temperature ranges only. In order to develop grain drying models that will encompass all ordinary drying air temperatures, the Michigan State University corn drying models use separate thin layer equations for different ranges of temperature.

Flood et al. (1969) developed the corn thin-layer equation for temperatures ranging from 2 to 22°C:

$$MR = \exp\ (-kt^{.664}) \qquad (2.2)$$

where:

$$MR = (M-M_e)/(M_o-M_e)$$

$$k = \exp\ (-xt^y)$$

$$x = (6.0142 + 1.453 * 10^{-4}(rh)^2)^{0.5}$$
$$- (1.8\theta + 32)(0.334*10^{-3} + 3*10^{-8}(rh)^2)^{0.5}$$

$$y = 0.125 - 2.197*10^{-3}$$
$$- (1.8\theta + 32)(2.3*10^{-5}(rh) + 5.8*10^{-5})$$

Thompson et al. (1968) developed the thin-layer drying equation for corn for the temperature range from 60 to 150°C:

$$t = A\ \ln(MR) + B(\ln(MR))^2 \qquad (2.3)$$

where:

$$A = 0.00488\theta - 1.86178$$

$$B = 427.36\ \exp\ (-0.033\theta)$$

Other thin-layer equations for corn, such as the Troeger and Hukill, the Muh, and the Misra have been compared by Rugumayo (1979).

Fontana (1983) compared various thin-layer equations for rice and found that an equation proposed by Wang and Singh

(1978) produced the best results for medium-grain rice. This equation has the same form as the thin layer equation developed by page (1949).

The thin-layer drying equation for medium grain rice by Wang and Singh (1978) is:

$$MR = \exp(-X*tm**Y) \qquad (2.4)$$

where:

$X = 0.01579 + 0.0001746*T - 0.01413*rh$

$Y = 0.6545 + 0.002425*T + 0.07867*rh$

tm = drying time (minutes)

T = air temperature (°C)

2.7.2 Deep-bed Drying Models

The Michigan State University grain dryer simulation models were developed for corn by Bakker-Arkema et al. (1974). Since the models are based on the fundamental laws of heat and mass transfer, they can be used to predict the heating or cooling with drying or moisture adsorption of other grains and biological products that satisfy the basic assumptions of the models.

In developing the Michigan State University grain drying models, Bakker-Arkema et al. (1974) had to make the following assumptions:

1. the shrinkage of grain bed due to drying is negligible

2. the temperature is uniformly distributed within each kernel
3. there is no particle-to-particle conduction
4. the airflow and the grainflow are plug-type
5. there is no heat loss or gain through or by the wall
6. $\delta T/\delta t$ and $\delta H/\delta t$ are negligible compared to $\delta T/\delta x$ and $\delta H/\delta x$
7. the heat capacities of moist air and of grain are constant during the short time periods.

2.7.2.1 Fixed-bed Model

Brooker et al. (1974) stated that the fixed-bed grain-drying model was developed based on the ideas of Schuman (1929), Van Arsdel (1955), Klapp (1961), and Bakker-Arkema et al. (1967). Four unknowns must be solved in the model. The unknowns are:

1. M - the kernel moisture content
2. H - the humidity ratio
3. T - the air temperature
4. θ - the product temperature.

Four energy and mass balances are made on a differential volume (Sdx), located at an arbitrary location in the fixed bed, to solve the unknown variables.

1. on the energy of the air

energy out = energy in - energy transferred by convection

$$\frac{\partial T}{\partial x} = \frac{-ha}{G_a c_a + G_a c_v H}(T-\theta) \qquad (2.5)$$

2. on the enthalpy of the product

energy transferred = change in internal product energy
- energy of evaporation

$$\frac{\partial \theta}{\partial t} = \frac{ha}{\varrho_p c_p + \varrho_p c_w M}(T-\theta) + \frac{h_{fg} + c_v(T-\theta)}{\varrho_p c_p + \varrho_p c_w M} G_a \frac{\partial H}{\partial x} \qquad (2.6)$$

3. on the humidity of the air

moisture transferred = moisture in - moisture out

$$\frac{\partial H}{\partial x} = -\frac{\varrho_p}{G_a}\frac{\partial M}{\partial t} \qquad (2.7)$$

4. on the moisture content

$$\frac{\partial M}{\partial t} = \textit{an appropriate thin layer equation} \qquad (2.8)$$

The boundary and initial conditions are:

a. $T_{(0,t)} = T_{inlet}$

b. $\theta_{(x,0)} = \theta_{initial}$

c. $H_{(0,t)} = H_{inlet}$

d. $M_{(x,0)} = M_{initial}$.

2.7.2.2 In-bin Counterflow Model

The in-bin counterflow model is a variation of the fixed-bed model. In the in-bin counterflow dryer, a bed of grain is held in the bin while heated air is blown upwards from the plenum through the bed. When the 7.5 to 11 cm bottom layer of the bed dries to a predetermined moisture content, it is removed by the sweep auger. All the other layers above will move down one layer deep, accordingly. In the simulation, the conditions of grain in these layers are maintained and move down with the layers as drying progresses. The removal of this bottom layer reduces the bed depth instantaneously. The airflow rate is then increased due to the shortening of the bed depth. If batches of wet grain are added at the top of the bed, as in the case of refilling, the airflow rate adjusts according to new bed depths.

The drying process is simulated using the MSU fixed-bed model, equations (2.5) to (2.8) (Bakker-Arkema et at., 1974). For the drying air temperatures of 71°C or less, the Troeger and Hukill (1970) thin layer equation is employed. When drying air temperatures higher than 71°C are used, the Thompson et al. (1968) equation is employed. The DeBoer equations are used to determine equilibrium moisture contents which are needed for the thin layer equations. To solve the fixed-bed model, the finite difference technique is applied.

2.7.2.3 Concurrentflow Model

The same assumptions as those for the fixed-bed model are made when solving the concurrentflow model. Heat and mass balances are made on an elemental volume of the dryer (Sdx) which results in four total differential equations. The differential equations are solved by the Runga-Kutta or the Adams-Moulton technique (Bakker-Arkema et al. 1974). The four equations of the concurrentflow drying model are:

$$\frac{dT}{dx} = \frac{-ha}{G_a c_a + G_a c_v H} (T-\theta) \qquad (2.9)$$

$$\frac{d\theta}{dx} = \frac{ha}{G_p c_p + G_p c_w M}(T-\theta) - \frac{h_{fg} + c_v(T-\theta)}{G_p c_p + G_p c_w M} G_a \frac{dh}{dx} \qquad (2.10)$$

$$\frac{dH}{dx} = -\frac{G_p}{G_a}\frac{dM}{dx} \qquad (2.11)$$

$$\frac{dM}{dx} = \textit{an appropriate thin layer equation} \qquad (2.12)$$

2.7.3 Equilibrium Moisture Content

The moisture content which the grain can achieve during drying is limited by the equilibrium moisture content of the grain under the particular drying air condition. In order to dry the grain to a lower moisture content, the equilibrium moisture content must be lowered by increasing the drying air temperature, decreasing the relative humidity, or both. The thin-layer equations in the dryer models must be used with the appropriate equilibrium moisture content equations to accurately predict the grain moisture content.

Various equilibrium moisture content equations have been developed for various grains. Brook and Foster (1981) recommended two equations:

a) the Henderson-Thompson Equilibrium Moisture Content Equation

$$Me = [(\ln(1-rh))/(-K(T+C))]^{1/N} / 100 \qquad (2.13)$$

where:

for y. dent corn, K = 0.000086541, N = 1.8634, C = 49.810

for rough rice, K = 0.000019187, N = 2.4451, C = 51.161

b) Chung-Pfost Equilibrium Moisture Content Equation

$$Me = B - C \ln [-1.98(T + A)\ln(rh)] \qquad (2.14)$$

where:

for y. dent corn, A = 30.205, B = 0.379212, C = 0.058970

for rough rice, A = 35.703, B = 0.325535, C = 0.046015

2.7.4 Airflow and Static Pressure

The airflow in a bin of grain decreases when the grain depth is increased. Mwaura (1984) simulated the airflow and static pressure changes for an in-bin counterflow dryer by equating the characteristic fan equation, obtained from the manufacturer, and the equation relating pressure drop and corn resistance to airflow, derived from (Hukill and Shedd, 1955).

The characteristic fan (centrifugal) equation is:

$$Y = a - \beta P^{c} \qquad (2.17)$$

where:

Y = volumetric airflow rate, m^3/min

P = pressure, kPa

For the fan used in the in-bin experiments:

a = constant, 368.81 m^3/min

$\beta = 80.87, \quad 0.0 < P < 1.9$

$\beta = 56.23, \quad 1.9 \leq P < 2.4$

$c = 1.17, \quad 0.0 < P < 1.9$

$c = 1.95, \quad 1.9 \leq P < 2.4$

The equation relating pressure drop and airflow through corn is:

$$P = (7 \times 10^{-3}\ D\tau y) / (\ln(1 - 0.512\ y)) \qquad (2.18)$$

where:

y = airflow rate, $m^3/min - m^2$

D = depth of corn, m

τ = fines factor (1.3 to 1.75, corn at the Kalchik Farm).

Fontana (1983) used the graph of airflow and pressure drop through rough rice, compiled by Steffe et al. (1980) from various authors, to determine the suitable equation and constants for the concurrentflow dryer simulation model.

The pressure drop equation for rice is of the form:

$$SP = a\ Q^{\ b} \qquad (2.19)$$

where:

SP = pressure drop, Pascal/meter

Q = airflow rate, $m^3/s/m^2$.

For medium grain, rough hulled, 0.66% impurities:

M.C. = 24.4% a = 4487.0, b = 1.4715,

M.C. = 12.7% a = 5309.0, b = 1.4853.

For medium grain, smooth hulled, 0.88% impurities:

M.C. = 27.6% a = 7319.0, b = 1.5006,

M.C. = 12.7% a = 7419.0, b = 1.4631.

The above data were obtained from studies by Henderson and Parsons (1974).

2.8 Economic Analysis

Smith (1968) observed that in the design of equipment and facilities, the main design criteria include function, economy, safety, and reliability. It is interesting to note that with time, there is a tendency for the design criteria to change from predominantly functional to predominantly economic. In deciding on a most suitable facility, such as a commercial rice drying complex, the engineer should consider alternatives. It is essential that in finding the best system, he has economy as an important criterion of design.

There are numerous methods of making economic comparisons of equipment and facilities. The traditional method of fixed and variable costs analysis (DIRTI method) has drawbacks. It does not explain cash flow requirements, financing or income tax effects, also, low investment costs can have a drastic influence on the ranking of alternatives even though the operating costs are high (Skees et al. 1979). A more realistic method of making an economic comparison between alternatives is capital budgeting or life-cycle costing. The annual net cash flow and the net present value of the different alternatives are compared. Factors, such as the inflation rate, interest rate, life of loan, capital depreciation schedule, investment tax credit, and income tax rate are accounted for in the analysis. By reducing all costs to a common present-worth basis, investments with different annual flow of expenses and/or incomes may be readily compared (Silva 1980).

Herbst (1982) defined capital investment projects that generate net cash inflows as major projects, and those that do not in themselves directly generate cash flows as component projects. While major projects strive to maximize value, component projects achieve net cash flows by minimizing costs for a given level of cash revenue. Herbst also stressed that "cost reduction may be considered a positive cash flow because it represents the elimination of an opportunity cost". An investment in a dryer is usually a component project.

In this dissertation, a computer program, Telplan 3 (Harsh 1972) which employs the net present value capital budgeting, will be used to compare the economics of the rice drying systems studied. Budgeting and discounted cash flows are well suited to analyze the economics of investing in new technology, to generate new income, reduce costs, or meet a firm manager's goal.

The Telplan capital investment model makes several assumptions of economic factors based on known current and forecasted future conditions. Values are assigned to the following factors:

a) the annual inflation rates of cost savings (or income generated), labor costs, fuel and oil costs, repair costs, supply costs and new machine costs
b) the insurance and housing costs as percentages of the inventory value at the start of each year
c) the oil and lubrication costs as a percentage of the fuel cost
d) the associated equipment repair cost as a percentage of the associated equipment fuel cost
e) the annual percentage rate of increase in the use of the investment.

If the conditions change, or better predicted values for the future become available, the original assumptions can be changed.

The validity of the output depends on the accuracy and reliability of these assumptions. Also, the input values such as the initial investment, operating costs, cost savings, etc. must be accurate and reliable for the analysis to produce useful results.

3. EXPERIMENTAL INVESTIGATIONS

Two mechanical systems for drying rice, currently used in the U.S., are chosen for this study. The in-bin counterflow dryer is employed mainly for on-farm drying. The high capacity multi-stage concurrentflow dryer is suited for large grain elevators. With dryer under-capacity being a major problem at the Malaysian governmental rice complexes during the wet season, these dryers are possible alternatives for future expansion of drying facilities.

Drying experiments were carried out with a commercial in-bin counterflow dryer at a farm and a commercial three-stage concurrentflow dryer at an elevator. Due to schedule and sponsorship constraints, it was not possible to operate the in-bin counterflow dryer with rice. Therefore, the in-bin counterflow dryer was tested with corn in Michigan. The experimental results of the in-bin counterflow dryer were used to validate the Michigan State University simulation model of the dryer. The model was then changed from corn to rice. This is possible because the drying model is based on fundamental laws of heat and mass transfer, and can be used to simulate the drying of any biological material by employing the proper thin layer equations and the appropriate material characteristics.

Rice drying experiments were carried out with a concurrentflow dryer at Cortina, CA., in the rice-producing region of California, the Sacremento Valley. The Michigan State University rice concurrentflow dryer simulation model was validated with the experimental results, and used to carry out analyses that could not be carried out with the real dryer.

3.1 In-bin Counterflow Drying of Corn

This study was conducted in October and November 1984, at the Kalchik Farms in Bellaire, Michigan.

3.1.1 The Shivvers In-bin Counterflow Dryer

The Shivvers in-bin counterflow dryer, consisting of a metal bin 5.49 m in diameter and 4.57 m high, was employed in the study. Heated air is blown through the perforated floor into the grain, and is exhausted at the top of the bin. A tapered sweep auger conveys a layer of dried grain to the center of the bin where a vertical auger transfers the grain via a horizontal transport auger to the cooling bin. The sweep auger is activated by the temperature probe which monitors the temperature of the bottom drying layer. Ambient air is blown through the grain in the cooling bin at a low air flow rate of 0.5 to 1 $m^3/min\text{-}m^2$, in order to temper, cool, and further reduce the moisture content of the grain by 2 to 3%. The tempering period is usually between 12 to 16 hours.

3.1.2 The Shivvers Comp-u-dry

The Shivvers Comp-u-dry (Computerized Dryer Control) operates as a parallel system to the existing dryer control. Grain is drawn from the bottom of the drying bin through a duct system into a chamber where the moisture content is determined. The computer has a readout display, and a strip printer which maintains a recorded history of the drying process. Drying is programmed by entering the final moisture content and the maximum plenum temperature desired in the computer. The tapered sweep auger of the dryer is activated when the moisture content of the sample is below the set value. The unloading of the dried grain continues until a sample with a moisture content higher than the set value is obtained. Sampling frequency depends on the difference between the measured and the set moisture content. It varies between 5 and 45 minutes for the set tested at the Kalchik Farms.

3.1.3 Plenum Insulation

The transition duct from the heater to the plenum and the plenum itself were covered by urethane foam, 5 cm thick. This exercise is to determine the amount of energy that can be saved by reducing the heat loss from the surfaces of the plenum and the transition duct to the ambient.

3.1.4 Procedure

Four drying tests of Pioneer 3901 corn were carried out. Test1 and test2 were made during the week of 10/16/84. No insulation was used on the dryer for these two tests. Test1 employed the Comp-u-dry to control the unloading of dried grain while test2 used the temperature probe to activate the sweep auger.

Test3 and test4 were carried out during the week of 11/12/84. The transition duct and the plenum were insulated. Test3 did not utilize the Comp-u-dry system, test4 did.

During the drying trials, samples of corn entering and leaving the dryer and after cooling were collected. The corn temperature of the samples was measured using a thermocouple-type thermometer. The moisture content of the samples was determined by a capacitance-type Dickey John moisture meter. Subsequently, the samples were tested for moisture in the laboratory using the standard oven method (72 hours at 103°C). The initial moisture contents of the samples in test1 and test2 varied from 35 to 36%, while in test3 and test4, they ranged from 26 to 27%.

For the energy consumption calculations, the dry and wet bulb temperatures of the ambient air entering the heater and of the exhaust air exiting the dryer were measured at regular intervals with a sling psychrometer. The plenum and the probe temperatures were recorded. During all the tests, the plenum temperature was maintained between 80 and 82°C.

The static pressure was recorded at regular intervals. The static pressure was used with the fan curve and the airflow resistance of corn equation to determine the airflow rate.

To calculate the energy usage, the amount of propane used was determined by refilling the gas tank. KWh meters recorded the electricity used by the fans and the augers.

The depth of dried corn was measured at the end of each drying run to indicate the volume and hence the weight of dried corn. For test1 and test2, the total amount of corn dried was measured on a scale.

3.2 Concurrentflow Drying of Rice

Tests on the concurrentflow dryer were carried out in October, 1985 in Cortina, California. Three three-stage concurrentflow dryers manufactured by Blount, Inc., Montgomery, Alabama, were studied drying medium grain rice.

3.2.1 The Blount Three-stage Concurrentflow Dryer

Each dryer measures 3.66 m x 3.66 m and has a total height of about 35 m. The top stage dryer is 1.1 m long, the middle stage dryer 1.2 m, and the bottom stage dryer 1.4 m. The depth of the counterflow cooler is 1.7 m. All the tempering zones are 5.2 m. The fans for the top and the middle stage dryers have a 93 kW motor each. A 75 kW motor is used for the third stage and a 37 kW for the cooling stage. The airflow for each stage can be controlled by valving air in the inlet ducts to the centrifugal fans. Propane gas was used as fuel for the heaters.

The operation of the concurrentflow dryer is described in section 2.6.2.

3.2.2 Procedure

The concurrentflow dryers were studied during actual commercial operation. Most of the rice dried was medium grain, and thus, this study concerns only with the drying of medium grain rice.

With the three dryers operating, the drying capacity of the elevator was 150 to 200 t/hour. Therefore, large amounts of rice from several farms were handled at the elevator daily. To represent the large daily rice delivery, samples were taken at intervals from the delivery trucks and tractors. The moisture content of the samples was measured with a resistance type moisture meter. The samples were then slowly dried in the sample dryer (air temperature of about 32°C) to about 12 to 13% moisture content. The dried samples were kept in sealed plastic containers for 48 hours before conducting the milling tests.

Wet rice received at the elevator, after being sampled and weighed, was cleaned and conveyed to concrete holding tanks. During drying, the wet rice was conveyed from the holding tanks to the top of the dryer and from the bottom of the dryer back to the tanks by a computer controlled conveying system. Samples of incoming and outgoing rice were scooped at the sampling point of the conveyor. These samples were dried in the sample dryer to the prescribed moisture content for milling tests.

The drying conditions of the concurrentflow dryer were conveniently recorded from the control panels of the dryer. The dryer operator, working in shifts, recorded the drying conditions every thirty minutes and sampled all rice going in and leaving the dryer throughout the entire season. Thermocouple sensors run from the panel to the burners and to various locations in the grain bed to measure the air and grain temperatures. For the first pass drying of wet rice, the inlet air temperature of the top stage was maintained between 105 to 110°C; the middle stage 80 to 85°C; the bottom stage 70 to 75°C. The counterflow cooler was not run during the 1985 season. For the second pass drying of rice, the inlet air temperature of each stage was reduced by about 5°C to minimize heat and moisture stresses on the kernels.

The static pressures developed by the various fans through the rice beds were remotely read at the control panels. The static pressures of the top, middle, and bottom stages of all the three dryers were maintained at about 2.5, 3.0, and 3.5 kPa, respectively. Airflow rates are calculated from the static pressure readings.

The dry bulb and the wet bulb temperatures of the ambient air in the area of the dryers were measured with a sling psychrometer at various times of the day and for the different days of the drying season. The average ambient air temperature and relative humidity are calculated from these measurements. The temperature of an average day ranged from about 12 to 27°C and the relative humidity ranged from about 20 to 60%.

The total amount of rice dried by the three concurrentflow dryers was added up from records of the daily receipts of the facility. The total amount of propane gas used are also added up from gas purchases. Checks on the gas storage tank, which holds 20,500 gallons, were made at some intervals to measure usage over short durations. Electricity usage was not recorded as it accounts for less than 5% of the total energy in drying (Bakker-Arkema et al. 1981). From the drying log kept by the dryer operators, the total time the dryers were operating is determined. All these totals enable the calculation of the average capacity and the rate of energy usage by the dryers.

3.2.3 Rice Milling-yield Determination

Paddy or rough rice is rice with the bran layers and the hull intact. In order to obtain white rice, rough rice has to be husked to remove the hull and then whitened by scrapping off the bran layers. Various types of large scale hullers, whitening cones, and polishers are used to process white rice from paddy kernels by commercial rice millers. In the laboratory, small sample shellers and mills are used to duplicate the actual milling conditions of the average commercial mills. In this study, the McGill rice sample sheller and the McGill miller No. 3 were used to carry out the milling tests (USDA 1976).

If 100 kg of rough rice were completely husked, about 20 kg of hulls would have been separated from approximately 80 kg of brown rice, rice kernel with the bran still intact (Henderson 1976). When the 80 kg of brown rice is whitened, about 70 kg of white rice and 10 kg of bran and polish are obtained. Part of the white rice will be whole kernels while the rest will consist of broken kernels of various fractions of the whole. The United States Standards for rough rice defines whole kernels or head rice as unbroken kernels of rice and broken kernels of rice which are at least three-fourths of an unbroken kernel (USDA 1976). The milling yield is defined as an estimate of the quantity of whole kernels and total milled rice (whole and broken kernels combined) that are produced in the milling of rough rice to a well milled degree. Commercial rice millers are more concerned with head rice than total milled rice because of the low value of broken rice, one third to half the value of head rice (Steffe et al. 1980).

Mill yield determinations were carried out based on USDA recommendations. The rough rice samples to be tested were dried to between 12 and 13% moisture content. 1000 g sample of rough rice were weighed, cleaned in a dockage machine, and then used for each milling test.

The McGill laboratory rice sheller was adjusted to the proper setting before the beginning of the milling tests. The hopper feed was adjusted such that 450 to 500 g of rice passed through the sheller per minute. For medium grain rice, the dial was turned to a setting of about 23. Slight adjustments were then made such that after shelling, only 3 to 4% of paddy kernels were left unshelled. The sheller was turned on before each sample was poured in and turned off only after the entire sample had cleared the sheller. Each sample was passed through the sheller once. The brown rice from each sample was weighed and then milled.

The U.S. standards for rice defines milling as the removal of practically all of the germs and bran layers from kernels of rice. The McGill miller No. 3 was used for milling the brown rice samples. Before the samples were milled, the equipment was warmed up. Approximately 750 g of milled rice was poured in the milling chamber and a 2-pound weight was placed on the weight holder. Three consecutive 30-second runs were made to warm the mill. The mill was then thoroughly cleaned.

Milling of the rice samples proceeded, using a two-bar, 3/64-inch oblong screen. Each sample was milled for two cycles of 30 seconds per cycle. For medium grain rice, western production, a 10-pound weight was placed on the weight holder for the first cycle, the milling cycle. The weight was reduced to 2 pounds for the second cycle, the brushing cycle. After the brushing cycle, the weights, the weight holder, the weight arm, and the saddle were removed and the mill was cleaned.

The milled rice from the milling chamber was transferred to a sample pan. The total milled rice was weighed and its percentage of the original 1000 g paddy rice sample was recorded. The milled rice was then divided using the Boerner divider until a small portion greater than 40 g was obtained. This small portion was run through a rice sizing device to separate out the broken kernels from the whole kernels. The broken kernels caught in the pockets of the sizing device were poured into a pan and further separated by hand to isolate whole kernels that were caught with the brokens. The whole kernels were weighed and their percentage as the weight of the portion of milled rice was calculated. This percentage was then converted to the percentage of whole kernels (head rice) over the original rough rice sample of 1000 g by multiplying with the percentage of the total milled rice.

4. RESULTS AND DISCUSSION

Experimental data were obtained from drying corn with the in-bin counterflow dryer, and drying rice with the concurrentflow dryer. Simulation results of drying rice with both dryers were also obtained. The Telplan 3 program is used in making economic comparison.

4.1 In-bin Counterflow Dryer

4.1.1 Experimental

Four drying tests were conducted in drying corn with the Shivvers in-bin counterflow dryer. The plenum chamber of the dryer was not insulated during tests T1 and T2, and insulated during tests T3 and T4. For tests T1 and T4, a Shivvers Comp-u-dry unit controlled the drying. A conventional controller was used for tests T2 and T3.

The ambient and drying conditions for the four tests are given in Table 4.1. Tests T1 and T2, carried out early in the harvesting season, started with very wet corn, 35 to 36% moisture content. The corn was dried to about 20% in the drying bin, and then aerated in the cooling bin where 1.5 to

2.5% moisture was further removed. Tests T3 and T4 were conducted later in the season when the harvested corn moisture content had fallen to about 27%. Drying decreased the moisture contents to about 17.5%, and cooling or dryeration reduced them further to between 15 and 16.5%.

The average ambient relative humidity was about 80 to 87% for tests T1 and T2 and about 71 to 74% for tests T3 and T4. The average ambient temperature was highest for test T1, 16.8°C and lowest for test T3, 0.7°C. During tests T2 and T4 the average ambient temperatures were 8.7°C and 7.7°C, respectively. During all the tests, the drying temperatures were maintained at about 80°C. Static pressures ranging from 0.2 to 1.3 kPa, were dependent on the depth of corn. The airflow rates varied with the changing static pressures. On the average, the airflow rates for the four tests ranged from 12.0 to 13.2 $m^3/min/m^2$. The drying times for the four tests were 35.45, 29.00, 17.35, and 18.83 hours.

Table 4.2 contains the amount of corn dried, the fuel and energy usage, the airflow volume, and the moisture removed during the different tests. About 47 t of wet corn was dried in test T1, 52 t in test T2, 44 t in test T3, and 50 t in test T4. More moisture was removed in the first two tests because the initial moisture contents were higher. Approximately 9.4 t of moisture was removed in tests T1 and T2, while 5.1 t and 5.6 t of moisture were removed in tests T3 and T4, respectively. Accordingly, more fuel and

Table 4.1 *Ambient and drying conditions during the testing of the Shivvers in-bin counterflow dryer with and without a Comp-u-dry controller, and with and without insulation.*

Drying Test	Corn Moisture Content (% w.b.)			Av. Rel. Humid. (%)	Av. Amb. Temp. (°C)	Av. Drying Temp. (°C)	Static Press. (kPa)	Airflow Rate (m^3/min /m^2)	Drying[a] Time (h)
	Wet	Dried	Cooled						
T1	36.1	19.9	18.5	80	16.8	79.5	1.3-0.2	11.0-14.9	35.45
T2	35.1	20.6	18.0	79	8.7	80.6	0.8-0.2	12.7-14.9	29.00
T3	27.2	17.7	15.1	74	0.7	79.4	1.0-0.2	12.0-14.9	17.35
T4	26.7	17.4	16.4	71	7.7	81.8	1.1-0.2	11.6-14.9	18.83

T1 Drying with Comp-u-dry, without insulation.

T2 Drying without Comp-u-dry, without insulation.

T3 Drying without Comp-u-dry, with insulation.

T4 Drying with Comp-u-dry, with insulation.

[a] *Dryer alone (without dryeration)*

Table 4.2 Total amount of drying and energy usage by the Shivvers in-bin counterflow dryer with and without Comp-u-dry and insulation.

Drying Test[a]	Total Wet Corn Dried (kg)	Total Fuel[b] Usage (L)	Total Elect.[c] Usage (kWh)	Total Energy Usage (kJ)	Total Airflow Volume (m^3)	Total Moisture[d] Removed (kg)
T1	46,678	1,692	399	46,944,432	603,037	9,440.6 (10,080.2)
T2	51,660	1,950	334	53,636,152	544,066	9,434.1 (10,773.0)
T3	43,972	1,155	221	31,849,721	321,997	5,075.8 (6,267.0)
T4	49,638	1,098	234	30,374,208	338,811	5,588.8 (6,115.7)

[a] Tests explained in Table 4.1.

[b] Propane gas was used to fuel the burner.

[c] Electricity for running fans and augers.

[d] Top and bottom values represent the before and after dryeration values, respectively.

Table 4.3 Average rate of drying and energy usage of the Shivvers in-bin counterflow dryer when drying corn.

Drying Test[a]	Av.[b] Drying Capacity (kg/h)	Av. Moisture Removed (kg/h)	Av. Fuel Usage (L/h)	Av. Elect. Usage (kWh/h)	Av. Energy Usage (kJ/h)	Total Drying Time (h)
T1	1,317	280.4	47.7	11.3	1,324,243	35.45
T2	1,781	325.3	67.2	11.5	1,849,522	29.00
T3	2,534	292.6	66.6	12.7	1,835,719	17.35
T4	2,636	296.8	58.3	12.4	1,613,075	18.83

[a] Tests explained in Table 4.1.

[b] All average values are for dryer only (without dryeration).

electricity were needed for tests T1 and T2 compared to tests T3 and T4.

The fuel (propane) burned during the tests was 1,692 L for T1, 1,950 L for T2, 1,155 for T3, and 1,098 for T4. To run the fans and the augers, 399 kWh of electricity were needed for T1, 334 kWh for T2, 221 kWh for T3, and 234 kWh for T4. Converting the fuel and electricity values to energy, the total energy needed for drying in tests T1, T2, T3, and T4 was 46,944,432 kJ, 53,636,152 kJ, 31,849,721 kJ, and 30,374,208 kJ respectively.

After drying, the hot corn was aerated with cool ambient air in the cooling bin. About 1.5 to 2.5 percentage points of moisture were removed in the cooling bin; no additional heat was used. This process is termed dryeration.

The total amount of moisture removed after drying and dryeration for the four tests was 10,080 kg for T1, 10,773 kg for T2, 6,267 kg for T3, and 6,116 kg for T4.

Dividing the total corn dried, fuel and energy usage, and moisture removed by the drying time for each test, results in the average rate of drying and energy usage. They are tabulated in Table 4.3. The average rates consider the drying in the drying bin and not in the cooling bin. The highest average drying capacity was obtained in test T4 (2,636 kg/h) while test T1 showed the lowest capacity (1,317 kg/h). Tests T3 and T4 have substantially higher drying capacities than tests T1 and T2. This is because the dryer removed 16.2

and 14.5 points of moisture in tests T1 and T2 and only 9.5 and 9.3 points of moisture in tests T3 and T4, respectively.

Comparing the two tests conducted with the plenum uninsulated (i.e. T1 and T2), T2 (which was controlled by the temperature probe) had a higher average rate of moisture removal than T1 which was controlled by the Comp-u-dry. However, with the insulated plenum, T4 which was Comp-u-dry controlled, had a slightly higher average rate of moisture removal than T3, which was temperature probe controlled. Thus, the rate of moisture removal does not seem to be affected by the use of the Comp-u-dry.

As expected, Table 4.3 shows that the average fuel usage, and hence the average energy usage is highest for the test with the highest rate of moisture removal, T2. Conversely, the lowest rate of energy usage is for the test with the lowest rate of moisture removal, T1.

The energy efficiency of drying in this study is defined as the amount of energy required to dry a unit mass of moisture. This is the preferred basis of comparison of the energy usage by a dryer because it is independent of the ambient conditions and the points of moisture removed. In tests T1 and T2, about 14.5 to 16 percentage points of moisture were removed by the dryer, whereas only about 9.3 to 9.5 percentage points of moisture were dried in tests T3 and T4. A biased comparison would result if energy per unit mass of grain dried were to be used as the basis.

Table 4.4 Energy efficiency of the Shivvers in-bin counterflow dryer after drying only.

Drying Test[a]	Fuel Energy Efficiency (kJ/kg H_2O)	Elect. Energy Efficiency (kJ/kg H_2O)	Total Energy Efficiency (kJ/kg H_2O)	Standardized[b] Energy Efficiency (kJ/kg H_2O)
T1	4,820	152	4,972	5,104
T2	5,558	127	5,685	5,104
T3[c]	6,118	157	6,275	4,800
T4[c]	5,284	151	5,435	4,641

[a] Tests explained in Table 4.1.

[b] Heat corrections are made for grain and ambient air temperatures to the common standard temperature of 15°C.

[c] With insulation.

Table 4.5 Energy efficiency of the Shivvers in-bin counterflow dryer after drying and dryeration.

Drying Test[a]	Fuel Energy Efficiency (kJ/kg H_2O)	Elect. Energy Efficiency (kJ/kg H_2O)	Total Energy Efficiency (kJ/kg H_2O)	Standardized[b] Energy Efficiency (kJ/kg H_2O)
T1	4,515	142	4,657	4,781
T2	4,867	112	4,979	4,470
T3	4,955	127	5,082	3,887
T4	4,829	138	4,967	4,241

[a] Tests explained in Table 4.1.

[b] Heat corrections are made for grain and ambient air temperatures to the standard temperature of 15°C.

Table 4.6 Fuel and Electricity costs per kilogram of water dried by the Shivvers in-bin counterflow dryer.

Drying Test[a]	Fuel Usage (L/kg H_2O)	Elect. Usage (kWh/kg H_2O)	Fuel[b] Cost (Cent/ kg H_2O)	Elect.[c] Cost (Cent/ kg H_2O)	Total[d] Cost (Cent/ kg H_2O)
T1	0.179	0.0423	3.634	0.410	4.044 (3.787)
T2	0.207	0.0354	4.202	0.343	4.545 (3.980)
T3	0.228	0.0435	4.628	0.422	5.050 (4.090)
T4	0.197	0.0419	3.999	0.406	4.405 (4.025)

[a] Tests explained in Table 4.1.

[b] Cost of propane gas for the 1989 season was 20.3 cents per liter.

[c] Cost of electricity for the 1989 was 9.7 cents per kWh.

[d] Values in () at bottom are for drying plus dryeration.

Values for the energy efficiency of drying are tabulated in Table 4.4. Energy efficiencies for drying plus dryeration are tabulated in Table 4.5. The propane gas and the electricity were the sources of energy. The energy efficiency for the four tests are 4,972 kJ/kg moisture for T1, 5,685 kJ/kg moisture for T2, 6,275 kJ/kg moisture for T3, and 5,435 kJ/kg moisture for T4. After dryeration, the energy efficiencies improved to 4,657 kJ/kg moisture for T1, 4,979 kJ/kg moisture for T2, 5,082 kJ/kg moisture for T3, and 4,967 kJ/kg moisture for T4.

The above energy efficiency determination is able to annul the effects of variations in points of moisture removed and total amounts of grain dried for the different tests. However, the variability in the initial grain temperature and in the ambient air temperature is not accounted for. To improve the energy efficiency criterion, a standard temperature is chosen.

In this study, 15°C is selected as the standard temperature. Appropriate additions and/or subtractions are made to the calculated energy for drying based on the temperatures of the grain and the ambient air. If the grain entering the dryer has an initial temperature less than 15°C, the energy necessary to bring the grain temperature to 15°C is subtracted from the energy of drying. Conversely, if the grain temperature is greater than the standard, the energy that must be removed to bring the grain temperature to 15°C, is added to the energy of drying. A similar correction is made for the ambient air. After making these energy corrections, the resultant energy efficiency is called the standardized energy efficiency.

The standardized energy efficiency of the dryer in the four tests is 5,104 kJ/kg moisture for both T1 and T2, 4,800 kJ/kg moisture for T3, and 4,641 kJ/kg moisture for T4. The standardized energy efficiency of drying plus dryeration is 4,781 kJ/kg moisture for T1, 4,470 kJ/kg moisture for T2, 3,887 kJ/kg moisture for T3, and 4,241 kJ/kg moisture for T4.

The costs of energy in drying are tabulated in Table 4.6. These costs are based on the 1989 cost of propane gas at 20.3 cents per liter and cost of electricity at 9.7 cents per kWh. For the dryer, the cost of energy per kg of moisture dried are 4.044 cent/kg moisture for test T1, 4.545 cent/kg moisture for T2, 5.050 cent/kg moisture for T3, and 4.405 cent/kg moisture. After dryeration, the energy cost for tests T1, T2, T3, and T4 fall to 3.787, 3.980, 4.090, and 4.025 cent/kg moisture, respectively, because of the low energy requirement in moving ambient air through the corn in the cooling bin.

From Table 4.4, the percentages of electrical energy used in drying over the total energy required are found to be 3.1% for T1, 2.2% for T2, 2.5% for T3, and 2.8% for T4. Compared to the fuel energy, the requirement for electrical energy is small. However, the unit cost of electricity is higher than that of propane. Table 4.6 tabulates the amount of propane and electricity used and their costs per kilogram of moisture removed. The percentage of electricity cost compared to the total energy cost for the tests is 10.1% for T1, 7.5% for T2, 8.4% for T3, and 9.2% for T4. Thus, although the electrical energy accounts for 3% or less of the total energy requirement of drying, its cost contributes more than 7% of the total energy cost.

Comparing on the basis of the standardized energy efficiency, Table 4.4 shows that operating the dryer without insulating the plenum requires the most energy per kg of moisture removed. Using either the Comp-u-dry or the grain temperature probe as the dryer controller, the dryer utilized about 5,104 kJ of energy for each kg of moisture removed. With the plenum insulated, the Comp-u-dry was able to affect a slight reduction in energy usage of about 3.3% compared to the case where the grain temperature probe acted as the controller. Considering this minimal effect of the Comp-u-dry on energy saving in the case of the insulated plenum and no effect in the uninsulated plenum case, it is concluded that on the whole, the Comp-u-dry has no significant effect on the energy usage in the in-bin counterflow dryer.

Several observations were made on the performance of the Comp-u-dry during the drying tests. In general, the Comp-u-dry controlled the dryer satisfactorily. However, there is room for improvement. The vacuum equipment and the moisture content measuring cell could not be readily disassembled, and the correct procedures were not adequately described in the instruction manual. Condensation occurred in the vacuum system because the cap on the vacuum line in the bin did not always close. A heat lamp only partially prevented the condensation. This caused problems with obtaining grain samples. At times, too much of the light material was pulled into the sample chamber, and this affected subsequent readings as the cell was not self-cleaning. The sampling time was about 80 seconds which is excessive. The frequency of obtaining sample was not suited to grain at a high moisture content; it resulted in returning too much grain to the dryer, reducing the drying efficiency. Overall, the control unit housing needs to be more sturdy and requires improvement. The fuses should be made more readily accessible; their replacement should be more adequately described. Lastly, there is a need for more clearly identified labels for removing and storing the control unit during the off-season.

The Comp-u-dry system added a degree of sophistication and complication to the in-bin counterflow dryer. Breakdown of the system occurred several times during the season. Although no serious faults were encountered, the operator using the Comp-u-dry to control the dryer should be technically adept if dealer assistance is unavailable.

Expectedly, insulating the plenum chamber of the dryer reduces heat lost to the environment and thereby increases the energy efficiency of the dryer. The standardized energy efficiency data in Table 4.4 show a reduction of 6 to 9% in the energy usage when the plenum was insulated. However, care should be taken in interpreting this result because experiments with the uninsulated plenum were conducted with corn of 35 to 36% moisture content while corn used in the insulated plenum tests had a moisture content of about 26 to 27%.

Dryeration removed 1.0 to 2.6% of moisture in cooling the hot grain from the dryer with ambient air. This is possible because in all cases, the grain leaving the dryer had moisture contents above the equilibrium moisture content for the respective ambient conditions. For example, in test T1, the grain left the dryer at an average moisture content of about 19.9%. The ambient air was at an average temperature of 17°C and 80% relative humidity. Data form Rodriguez-Arias (1956) indicate that the equilibrium moisture content of shelled corn when exposed to this ambient condition is approximately 16.3%. Thus blowing the ambient air through the grain at 19.9% will reduce the moisture content further.

The recommended airflow rate in dryeration is in the range of 0.4 to 0.8 $m^3/min\text{-}m^3$ grain (Brooker et al. 1974). The electrical energy required for the fan to move air at this very low rate is negligible compared to that required for drying. Dryeration, therefore, reduces the energy consumption per unit weight of moisture removed. The standardized energy

Table 4.7 Drying conditions of test T2 and test conducted by Silva (1980) in 1978.

Drying Test	Corn Moisture Content (% w.b.)			Av. Rel. Humid. (%)	Av. Amb. Temp. (°C)	Av. Drying Temp. (°C)	Static Press. (kPa)	Airflow Rate (m^3/min /m^2)
	Wet	Dried	Cooled					
T2	35.1	20.6	18.0	79	8.7	80.6	0.8-0.2	12.7-14.9
T(1978)	26.4	18.3	16.3	54-99	3.9-14.5	65.5-72.0	1.0-0.5	-

Table 4.8 Energy efficiency comparison (drying plus dryeration) of T2 and test conducted by Silva (1980) in 1978.

Drying Test	Total Wet Corn Dried (kg)	Total Fuel Usage (L)	Total Elect. Usage (kWh)	Energy Efficiency (kJ/kg H_2O)	Standardized Energy Efficiency (kJ/kg H_2O)
T2	51,660	1,950	334	4,979	4,470
T(1978)	62,000	1,419	818	4,699	4,548

Table 4.9 Ambient and drying conditions for testing the Shivvers in-bin counterflow dryer in English units.

Drying Test	Corn Moisture Content (% w.b.)			Av. Rel. Humid. (%)	Av. Amb. Temp. (°F)	Av. Drying Temp. (°F)	Static Press. (in. H_2O)	Airflow Rate (ft^3/min /ft^2)	Drying Time (h)
	Wet	Dried	Cooled						
T1	36.1	19.9	18.5	80	62.2	175.1	5.2-0.8	36.1-48.9	35.45
T2	35.1	20.6	18.0	79	47.6	177.0	3.2-0.8	41.7-48.9	29.00
T3	27.2	17.7	15.1	74	33.3	175.0	4.0-0.8	39.4-48.9	17.35
T4	26.7	17.4	16.4	71	45.9	179.2	4.4-0.8	38.1-48.9	18.83

T1 Drying with Comp-u-dry, without insulation.

T2 Drying without Comp-u-dry, without insulation.

T3 Drying without Comp-u-dry, with insulation.

T4 Drying with Comp-u-dry, with insulation.

Table 4.10 Results of the drying tests on the Shivvers in-bin counterflow dryer in English units.

Drying[a] Test	Total Wet Corn Dried (lb)	Total[b] Moisture Removed (lb)	Total Fuel Usage (gal)	Total Elect. Usage (kWh)	Av. Drying Capacity (lb/h)	Total Energy Efficiency (Btu/ lb H_2O)	Standard.[c] Energy Efficiency (Btu/ lb H_2O)
T1	102,908	20,813 (22,223)	447	399	2,903	2,138 (2,002)	2,211 (2,070)
T2	113,890	20,798 (23,750)	515	334	3,927	2,444 (2,141)	2,248 (1,968)
T3	96,942	11,190 (13,816)	305	221	5,587	2,698 (2,185)	2,102 (1,703)
T4	109,433	12,321 (13,483)	290	234	5,812	2,336 (2,135)	1,960 (1,791)

[a] Tests explained in Table 4.1.

[b] Values at top are for drying alone.
Values in () at bottom are for drying plus dryeration.

[c] Heat corrections are made for grain and ambient air temperatures to the common standard temperature of 60°F.

consumption per kg of moisture removed in the four tests were reduced by 6.3% for T1, 12.4% for T2, 19.0% for T3, and 8.6% for T4.

Silva (1980) tested the same in-bin counterflow dryer in the Fall of 1978. At that time, the Comp-u-dry was not available and the test was conducted without an insulated plenum. The test conducted by Silva (1980) is similar to test T2. The tests are compared in Tables 4.7 and 4.8. The ambient conditions of the tests are similar. However, Silva employed a lower drying temperature (i.e. 65.5 - 72.0°C compared to 80.6°C for T2). About 62 t of corn was dried by Silva while 51.7 t was dried during T2. T2 used more LP fuel, 1950 L compared to 1419 L; the Silva test utilized more than twice as much electricity. The calculated energy efficiency shows T2 using only about 6% more energy. The standardized energy efficiency shows an even closer similarity, T2 using 1.7% less energy than Silva's test. On the whole, the results of both tests are similar.

So far, all calculations are made in the S.I. units. In order to facilitate readers who are more familiar with the English units, the important tests conditions and the results of the drying experiments are converted to English units and tabulated in Tables 4.9 and 4.10.

4.1.2 Simulation

Mwaura (1984) used the Michigan State University fixed-bed drying model, proposed by Bakker-Arkema et al. (1974), to simulate the in-bin counterflow dryer. The in-bin counterflow dryer computer program simulates corn drying with the grain temperature probe controlling the activation of the sweep auger (refer to section 2.6.1). Drying tests T2 and T3 are simulated employing the Mwaura program.

One of the assumptions in the Michigan State University drying models is that there is no heat loss or gain through the bin wall. This favors drying experiment T3 because the plenum chamber in T3 was insulated while that in T2 was not. Thus, test T3 will be used to compare the experimental and the simulated data of the in-bin counterflow corn drying.

Results of tests T1, T2, and T4 are tabulated in Tables A.1, A.2, and A.3 in Appendix A.

4.1.2.1 Drying Conditions for the Simulation

Care needs to be taken to make the drying condition of the simulation as similar as possible to that of the experimental test T3. The experimental moisture content, the ambient temperature and relative humidity, and the drying air temperature are given in Table 4.1. The average initial temperature of corn entering the dryer (i.e. 5.7°C) is used in the simulation.

Test T3, like the other three tests, was conducted under normal farm operation. The in-bin counterflow dryer was operated as a continuous dryer with refilling depending on the rate of harvesting. It required about 40 to 50 minutes to spread a truck-load of corn on top of the drying bed. However, the simulation program assumes instantaneous refilling. The time of refilling in the simulation is the time mid-way in each refilling of the experimental drying.

Under normal operation, the in-bin counterflow dryer simulation program requires a constant amount of corn for each refill and a constant frequency of refill. By making minor modifications in the program, it was possible to simulate the refilling process of desired amounts and at desired times. In this simulation of T3, 4 refills of equal amounts of corn are made at varying intervals, thereby simulating a wagon-load arriving at the dryer after different periods.

The drying conditions and other input data to simulate test T3 are tabulated in Table 4.11.

4.1.2.2 Comparison of the Simulated and Experimental Results

Pertinent simulated output values of the in-bin counterflow drying of corn are summarized in Table 4.12 and compared with the experimental result of test T3.

The total drying time from the simulation is 17.59 hours

Table 4.11 Input data for the in-bin counterflow dryer computer program to simulate test T3.

Time of refills after the start of drying (h)	2.8 4.8 7.0 9.6
Amount of corn per refill (m^3)	10.71
Amount of dried grain removed per cycle (m^3)	3.28
Drying air temperature (°C)	79.4
Average ambient air temperature (°C)	0.7
Average ambient relative humidity (decimal)	0.74
Type of fuel used (L.P.Gas, biomass, etc.)	L.P.Gas
Average inlet grain temperature (°C)	5.7
Initial moisture content (% w.b.)	27.2
Testweight (kg/m^3)	640.7
Final moisture content (% w.b.)	17.7
Initial bed depth (m)	1.09
Fines factor (1 clean, 2 dirty)	1.2
Maximum drying time (h)	19.0
Output interval (m)	0.152
Hybrid drying factor (decimal)	1.0

Table 4.12 Comparison of experimental and simulated performance of the intermittent in-bin counterflow dryer.

Cycle No.	Cycle Time (h)		Capacity (t/h)		Airflow (cmm/m^2)		Moisture (%wb)		SECO[b] (kJ/kg H_2O)
	Exp	Sim	Exp	Sim	Exp	Sim	Exp	Sim	
1	1.85	2.25	1.42	0.93	12.8	13.4	18.8	17.6	2605
2	0.82	0.58	2.93	1.48	13.2	13.6	18.4	17.3	3286
3	0.92	0.58	2.61	2.09	13.0	13.1	18.2	17.0	3462
4	0.90	0.75	2.54	2.77	12.8	13.3	19.0	17.7	4303
5	0.92	1.77	2.49	1.18	12.9	13.6	18.7	17.6	4842
6	0.92	1.02	2.61	2.05	13.0	13.0	18.4	17.6	5531
7	0.90	0.51	2.67	4.11	12.8	13.2	18.4	17.6	5942
8	0.93	0.67	2.46	3.13	12.6	13.5	17.6	17.6	6187
9	0.88	1.37	2.73	1.53	12.1	13.0	18.0	17.6	6522
10	0.87	0.85	2.76	2.47	12.3	13.2	17.3	17.7	6678
11	0.87	0.76	2.63	2.77	12.4	12.7	18.0	17.7	7156
12	0.87	0.92	2.63	2.26	12.4	12.9	17.6	17.6	7457
13	0.80	1.52	2.72	1.37	13.2	13.1	16.2	17.6	7187
14	0.78	0.58	2.94	3.58	13.2	13.4	17.6	17.6	7522
15	0.82	1.41	2.65	1.48	13.6	13.6	16.4	17.6	7543
16	0.88	1.16	2.47	1.79	13.8	13.9	19.4	17.6	7592
17[a]	0.73	0.58	2.51	3.59	14.1	14.2	17.0	17.7	7894

whereas that of the experimental test was 17.35. Thus, there is a close agreement in the total drying time. Furthermore, the number of cycles in the experimental and the simulated tests are identical at 19.

The first cycle time is the duration between the start of the dryer and the beginning of the first transfer of the dried bottom layer of grain. Subsequent cycle times are durations between consecutive starts of the grain transfer process. This cycle time can be interpreted as the time needed to dry the bottom layer of the grain bed to the prescribed moisture content.

Table 4.12 shows that the first cycle times for both the experimental and the simulated runs are the longest. This is due to the initial period when the energy from the drying air is absorbed to increase the temperatures of the grain. Also the airflow rate is low since the grain depth is initially deep. This extended first cycle time allows the second layer to dry to a moisture content close to that of the bottom layer. Hence, after the first cycle, the second bottom layer will take a shorter time than normal to dry to the required moisture content. Table 4.12 clearly shows that the second cycle time is the shortest in each drying run.

The four refills to the dryer occur after cycles 2, 5, 8, and 10. These refills affect drying by increasing the bed depth with cold wet corn. The airflow rate is thus reduced. Excessive energy is not required to heat this new grain. The hot and humid air leaving the bottom layers transfers energy to the wet grain instead of being exhausted directly to the atmosphere. However, condensation can occur, and thus the top layers may increase in moisture content. Condensation and absorption of moisture by the top layers can also occur without refill if the initial bed depth is large enough.

The increases in cycle times due to refills for the simulated run are delayed for the first and fourth refills and immediate for the second and third refills. The cycle times of the experimental run are less fluctuating. This is because refilling is gradual in actual drying whereas refilling is instantaneous in the simulation.

The drying capacity is the mass of corn dried per unit time. For each cycle, the amount of dried corn transferred is constant for the simulated run and approximately constant for the experimental run. Thus drying capacity depends mainly on cycle time. Table 4.12 shows in both cases, the drying capacity varies inversely with the cycle time. Following the trends of cycle time, the drying capacities of the simulation fluctuate more than those of the experimental run. The average drying capacity of the experimental test T3 is 2.5 t/h while that of the simulation is slight lower (i.e. 2.2 t/h).

The airflow rate is dependent on the fan power and the resistance of the grain bed. In both runs, the airflow rates increase and decrease gradually as the bed depths decline and increase. The airflow rates are highest at the end of drying when the bed depths are lowest. For the experimental run, the highest airflow rate was 14.7 cmm/m^2. The highest airflow rate for the simulation run is 14.8 cmm/m^2.

The specified final moisture content of dried corn for the simulation run is 17.7%. The computer program stays within 1% of the prescribed final moisture content for all cycles except cycles 2 and 3 when the moisture contents fall to 17.3% and 17.0%, respectively. For the experimental test, the final moisture content of grain leaving the dryer fluctuated between 16.2 and 19.4 in the first 17 cycles. There was a seven-hour break from drying after cycle 17. When drying resumed, the final moisture contents for both cycles 18 and 19 fell to 14.7%. It is more difficult to control the final moisture content of the actual drying because the temperature of the grain is used as an indication of the moisture content. The average final moisture content for the experimental test T3 was 17.7% while that of the simulation run is 17.6%.

The last column of Table 4.12 presents the specific energy consumption or SECO of each cycle of the simulation run. SECO in the computer program is calculated as follows:

$$SECO = (G_{ai}\, C\, \Delta T \Delta t_i + E_i) / W_i \qquad (4.1)$$

where:

G_{ai} = airflow rate of the ith cycle (kg/h)

C = specific heat of air (kJ/kg °C)

ΔT = temperature difference between ambient and drying air (°C)

Δt_i = cycle time of the ith cycle

E_i = electrical energy used in the ith cycle (kJ)

W_i = water removed in the ith cycle (kg).

The specific energy consumption is the amount of energy required to evaporate 1 kg of water from the grain. Heat loss by the system is not included in this calculation. In the actual drying test it is only possible to calculate the average energy efficiency of drying. The sum of the total energy from propane and electricity used is divided by the total amount of water dried from the grain. In this calculation, heat losses can be included.

The SECO of the simulated drying run starts at 2,605 kJ/kg H_2O for the first cycle, and increases until it reaches 8,476 kJ/kg H_2O in the last cycle. The increase in SECO between consecutive cycles varies from 841 kJ/kg H_2O for cycles 3 and 4 to 21 kJ/kg H_2O for cycles 14 and 15. In fact, there is a decrease in SECO of 270 kJ/kg H_2O from cycle 12 to 13. Thus, there appears to be no pattern in the SECO values as drying progresses (except during the last few cycles).

Various factors affect the energy requirement of drying. As grain dries, the rate of moisture moving from the interior to the surface decreases. Thus longer time and more energy is needed to dry an equal amount of moisture at lower moisture contents. This phenomenon tends to increase the SECO as drying progresses. However, refilling and moisture condensation in the upper layers of the drying bed tend to present layers of higher moisture content for drying at later times. This will have a reducing effect on the SECO. Towards the end of drying, the grain bed has become shallow, and the heated air leaving the bed is no longer saturated. Therefore, SECO increases in cycles 16, 17, 18, and 19.

The specific energy consumption, in drying corn with the in-bin counterflow dryer, determined from the simulation run is 8,476 kJ/kg H_2O. The experimental energy consumption measured in test T3 was 6,275 kJ/kg H_2O. There is a reasonably close agreement between the two values.

4.1.2.3 Validation of the In-bin Counterflow Drying Model

The cycle times, the capacities, and the final moisture contents of corn of the actual drying test T3 and its computer simulation by the in-bin counterflow drying model compare favorably. The airflow rates of the experimental drying run are very close to those of the simulated run, cycle by cycle. There is an exact comparison of the number of cycles for both drying runs. Most importantly, the average SECO of the simulation matches well with the energy consumption of the experimental drying test. Thus, the in-bin counterflow drying model is a valid tool for testing the performance of the in-bin counterflow dryer.

The in-bin counterflow drying model simulates the drying of corn and uses as its base the Michigan State University fixed-bed drying model. The fixed-bed model is based on the fundamental laws of heat and mass transfer. Therefore, by changing the thin layer and the equilibrium moisture content equations to those for rice, by replacing the physical properties of corn with those of rice, and by changing the airflow equation, the modified in-bin counterflow dryer simulation model can be assumed adequate to simulate the in-bin counterflow drying of rice.

4.2 Concurrentflow Dryer

4.2.1 Experimental

Three three-stage concurrentflow dryers of identical make, dimension, and capacity were tested under commercial operating conditions of a rice elevator. All dryers were operated simultaneously and set to similar drying temperatures, airflow rates, and grain-flow rates. Collected samples of rice entering and leaving the dryers, enable the investigation of the average performance of the three dryers. The results and discussions in the following sections will therefore, pertain to the typical Blount 3.66 m x 3.66 m, three-stage concurrentflow dryer.

Early in the harvesting season, rice was received at the elevator with moisture contents above 24 % and had to be dried in four or more passes. Conversely, late in the season, only one pass was needed to dry harvested rice with low moisture contents of about 15 to 16 %. Drying experiments on the concurrentflow dryers were carried out during the mid-season's peak harvests, when the moisture contents of the rice received were about 22 to 24 %. Three passes were needed to dry this rice to storage moisture content of about 13 to 13.5 %. Typically, a 23 % moisture rice would be dried to about 19 % in the first pass, to about 16 % in the second pass, and to about 13.5 % in the final pass.

Fifteen drying tests were carried out; five tests for each of the three passes. The test durations ranged from 5 to 12 hours. During each test, a batch of rice with similar moisture content from the holding bins was passed through the dryers and then conveyed back to the holding bins or to the storage tanks.

The ambient and drying conditions for the experiments are tabulated in Table 4.13 and Table 4.14. The average temperatures of the ambient air are listed in Table 4.13; the temperature varied from 8 to 27°C. The temperature also changed during individual tests; in test 3, the ambient temperature varied the least, from 19 to 22°C, while in test 6, the temperature varied the most, from 23 to 13°C.

The relative humidity fluctuated the most during test 10,

Table 4.13 Average conditions of grain, ambient air, and dryer during the testing of the three-stage concurrentflow dryer.

Test No.	Amb. Temp. (°C)	Amb. R.H. (%)	Inlet Grain Temp. (°C)	Outlet Grain Temp. (°C)	Inlet Grain M.C. (% wb)	Outlet Grain M.C. (% wb)
1	16.1	33	24.4	34.4	23.5	19.2
2	17.8	37	25.0	36.7	22.0	18.8
3	20.0	33	24.4	34.4	23.2	18.9
4	20.0	33	24.4	33.3	22.6	18.9
5	17.2	30	26.7	36.1	23.3	18.1
6	17.8	37	33.3	37.8	20.4	16.5
7	17.2	38	36.7	34.4	20.1	15.6
8	18.3	32	34.4	34.4	19.2	16.2
9	18.3	32	35.6	35.6	18.6	15.4
10	17.2	30	33.9	37.8	18.6	14.7
11	17.2	38	35.6	37.2	17.4	14.1
12	20.0	33	33.9	35.6	16.2	13.3
13	18.3	32	35.0	36.7	15.9	13.7
14	17.8	41	35.6	31.1	14.6	13.4
15	18.9	46	35.6	32.2	14.2	13.5

Table 4.14 Average operating temperatures of the three-stage concurrentflow dryers during testing in Williams, CA.

Test No.	Top Stage			Middle Stage			Bottom Stage		
	Inlet Air Temp. (°C)	Exh. Air Temp. (°C)	Tempering Temp. (°C)	Inlet Air Temp. (°C)	Exh. Air Temp. (°C)	Tempering Temp. (°C)	Inlet Air Temp. (°C)	Exh. Air Temp. (°C)	Tempering Temp. (°C)
1	124.4	28.3	38.9	96.1	33.9	37.8	77.8	32.8	33.9
2	118.3	30.0	38.3	95.0	33.9	38.3	79.4	34.4	36.7
3	112.8	31.1	38.3	88.9	33.9	38.3	70.6	33.3	35.6
4	110.0	30.6	38.9	87.2	33.9	37.2	64.4	32.2	33.3
5	114.4	31.1	37.8	91.1	33.3	37.2	78.3	30.6	36.1
6	107.8	33.9	38.9	87.8	34.4	39.4	81.1	35.0	37.8
7	98.9	36.1	40.0	82.8	35.0	36.7	68.9	33.3	34.4
8	108.3	34.4	38.9	78.3	32.2	35.0	72.2	33.3	35.0
9	106.1	34.4	38.9	77.2	33.3	36.7	72.2	33.9	36.1
10	100.6	34.4	38.3	70.0	35.0	35.6	71.1	34.4	37.2
11	81.1	33.3	38.3	65.0	33.3	37.8	66.1	35.0	37.8
12	90.6	33.3	37.8	68.3	33.3	37.8	61.7	34.4	37.2
13	96.7	35.0	38.3	78.3	33.9	36.1	75.0	35.0	37.2
14	65.0	30.6	32.2	off	off	off	64.4	33.3	36.7
15	63.9	32.8	33.9	off	off	off	63.9	34.4	37.8

from 11 to 39 %. The least variation in relative humidity was observed in test 12, from 32 to 35 %. The average values, given in Table 4.13, are used in the drying calculations.

The inlet and outlet grain temperatures refer to the temperatures of grain entering and leaving the dryer. While, only average values are given in Table 4.13, they did not vary by more than 2°C in all cases. Similarly, the average values of the inlet and the outlet grain moisture contents stayed within 1 % of the average.

Throughout the experiments, the unload augers of the dryers were maintained at 35, 35, and 27 rpm for dryers 1, 2, and 3, respectively. This ensured that each dryer delivered a steady-state output of approximately 70.8 m^3 per hour of dried rice. Also maintained constant were the static pressures of the top, middle, and bottom stages of the three dryers at 2.5, 3.0, and 3.5 kPa, respectively. At these static pressures the airflow rates were 40.2, 37.0, and 37.9 $m^3/min/m^2$ in the top, middle, and bottom stages of each dryer.

The average inlet-air temperatures of the dryers are tabulated in Table 4.14. The temperatures are the averages of data recorded every half hour during an experiment. Expectedly, the individual recorded temperatures varied from the average. For example, the average (drying) inlet air temperature for the top stage in test 3 was 112.8°C. The actual recorded values varied from 104.4 to 118.3°C. The exhaust temperature of the top stage of the same test varied between 29.4 and 31.7°C while the tempering temperatures ranged from 35 to 40.6°C. Similar variations are found in the other dryer stages and other drying tests.

Table 4.14 shows that the inlet air temperatures used were highest in the top stage, and were reduced in the second and third stages. Higher temperatures were also used in the first drying pass when the grain moisture content was highest. This pattern of temperature selection is adopted in order to achieve the highest energy efficiency of drying while avoiding major head yield losses due to kernel checking. In the first pass, drying temperatures of 110 to 124°C were used. Drying temperatures of 99 to 108°C were used in the second pass and 64 to 97°C in the third pass. The temperatures for the middle and the bottom stages of the first, second, and third passes were 87 to 96°C and 64 to 79°C, 70 to 88°C and 69 to 81°C, and 65 to 78°C and 62 to 75°C, respectively. The middle stage burner in tests 14 and 15 was turned off because the inlet moisture content of the rice was very low (i.e. 14.6 and 14.2%).

It is important to note that in the first pass, very high drying air temperatures were used. In test 1, the average drying air temperature of the top stage was 124.4°C and yet, the average tempering temperature was only 38.9°C. This is because most of the sensible heat of the drying air is quickly transformed into latent heat of evaporation due to the high rate of drying of very wet rice. The efficient use of heat in this stage is also evidenced by the low average exhaust air temperature of 28.3°C. Thus, high drying capacity and efficient use of energy without excessive thermal stress to the rice kernel is achieved in this stage. At lower stages or later passes when the rate of drying of the rice fell, the drying temperatures were reduced appropriately in order to reduce heat loss through the exhaust and to maintain low kernel temperatures to avoid excessive stresses in the kernels.

The volumetric grain-flow rate was maintained constant throughout a drying test. However, the grain mass-flow rate decreased as the bulk density decreased with the increasing loss of moisture as drying progressed. From the mass-flow rate and the inlet and outlet grain moisture contents, the rate of moisture removal is determined. These values are tabulated in Table 4.15. Expectedly, the rates of drying are highest for the first pass tests 1 to 5, averaging 2.5 t moisture per hour per dryer. The average rate of drying for the second-pass tests is 2.05 t moisture per hour and that of the third-pass tests is 1.07 t moisture per hour.

The fuel used to fire the burners was propane gas. The rate of fuel usage was determined by recording the drop in the fuel level in the storage tank and dividing it by the hours the dryers were operating. The average fuel usage rate per dryer and the calculated energy usage are given in Table 4.15. Fuel usage in tests 1 to 13 ranged from 265.0 to 314.2 L per

Table 4.15 Energy efficiency of the three-stage concurrentflow dryer.

Test No.	Inlet Grain M.C. (% wb)	Outlet Grain M.C. (% wb)	Grain-flow Rate (t/h)	Moisture-removal Rate (t/h)	Fuel-usage Rate (L/h)	Energy-usage Rate (MJ/h)	Energy Efficiency (kJ/kg H_2O)	Standard.[a] Energy Efficiency (kJ/kg H_2O)
1	23.5	19.2	46.38	2.61	314.2	8406.7	3225	3163
2	22.0	18.8	46.15	1.89	314.2	8406.7	4440	4190
3	23.2	18.9	46.21	2.59	291.5	7799.0	3014	2625
4	22.6	18.9	46.21	2.21	291.5	7799.0	3531	3078
5	23.3	18.1	45.93	3.11	265.0	7090.0	2277	2157
6	20.4	16.5	45.13	2.21	314.2	8406.7	3802	3593
7	20.1	15.6	44.68	2.52	314.2	8406.7	3341	3209
8	19.2	16.2	44.91	1.67	291.5	7799.0	4678	4344
9	18.6	15.4	44.57	1.75	291.5	7799.0	4452	4137
10	18.6	14.7	44.23	2.12	265.0	7090.0	3346	3180
11	17.4	14.1	43.89	1.75	314.2	8406.7	4795	4612
12	16.2	13.3	43.20	1.50	291.5	7799.0	5216	4603
13	15.9	13.7	43.66	1.14	291.5	7799.0	6829	6363
14	14.6	13.4	43.32	0.61	140.1	3747.6	6157	5453
15	14.2	13.5	43.43	0.35	-	-	-	-

[a] Grain and ambient air temperatures corrected to 15°C.

Table 4.16 Effect of the concurrentflow dryer on the milling yield of test samples.

Test No.	Brown Rice (%)	Total Yield (%)	Head Yield (%)	Head Yield Drop (%)
1 IN	80.2	69.2	56.1	
1 OUT	80.8	69.2	54.6	1.5
2 IN	80.8	69.6	58.2	
2 OUT	79.8	68.4	58.2	0.0
3 IN	80.4	69.2	57.6	
3 OUT	81.4	69.4	57.1	0.5
4 IN	81.0	69.2	60.4	
4 OUT	80.8	69.0	59.9	0.5
5 IN	80.8	69.0	58.9	
5 OUT	80.8	69.0	57.8	1.1
6 IN	80.8	69.9	56.4	
6 OUT	80.4	69.2	53.5	2.9
7 IN	79.0	66.8	53.4	
7 OUT	80.2	68.4	53.7	-0.3
8 IN	81.6	70.2	59.0	
8 OUT	81.2	69.0	56.5	2.5
9 IN	81.2	69.6	59.6	
9 OUT	81.6	69.6	56.2	3.4
10 IN	82.0	69.8	57.9	
10 OUT	81.2	69.8	54.5	3.4

Table 4.16 (Cont'd.).

Test No.	Brown Rice (%)	Total Yield (%)	Head Yield (%)	Head Yield Drop (%)
11 IN	81.8	72.0	54.1	
11 OUT	80.8	68.8	52.1	2.0
12 IN	80.8	69.0	55.1	
12 OUT	80.4	69.2	57.6	-2.5
13 IN	80.8	68.6	54.9	
13 OUT	81.2	69.6	55.9	-1.0
14 IN	82.6	71.2	61.8	
14 OUT	82.0	69.8	59.9	1.9
15 IN	82.6	70.8	58.0	
15 OUT	81.2	68.4	55.6	2.4

Each milling yield is given as a percentage of the 1000 g rough rice sample used in each milling test.

hour. Only 140.1 L per hour fuel was used in test 14. Fuel usage in test 15 was not determined.

The energy usage given in Table 4.15 is calculated from the fuel usage multiplied by a heat value of propane of 26,756.8 kJ per L. From the energy usage and the moisture removal rate, the energy efficiency can be calculated. In order to nullify the effect of ambient temperature, the energy efficiency of each test is standardized to the common temperature of 15°C. Energy corrections are made to bring the inlet grain temperature and the ambient air temperature to the standard temperature.

The average standardized energy efficiency, calculated from Table 4.15, is found to be 3,908 kJ per kg water removed. This compares well with the results obtained by Fontana (1983).

Calculating the average energy efficiency of drying for the 3 passes separately, it is found that the energy efficiencies are 3,043, 3,693, and 5,258 kJ per kg water removed for passes 1, 2, and 3, respectively. The dramatic increase in energy requirements of drying as the rice becomes dryer, is due to the lower moisture content of the rice and the lower operating temperatures of the third pass.

The results of the milling tests are tabulated in Table 4.16. The brown rice, the total white rice, and the head rice yields are given as percentages of the initial rough rice milling sample of 1,000 g. It is important to note that in each drying test, the batch of rice being dried came from many different farms. With non-homogeneous rice samples, the milling yields obtained show trends on the effect of drying with the concurrentflow dryer on head-yield losses.

The brown rice yield showed no definite trend, and varied from 79.0 % for the inlet rice of test 7 to 82.6 % for the inlet rice of both tests 14 and 15. The average yield of brown rice was 81.0 %. The total yield (white milled rice) also varied randomly from, 68.4 to 72.0 %, and averaging 69.4 %.

One of the most important concerns in drying rice is the effect on the head yield. By determining the head yields of samples entering and leaving the dryer, the drop in head yield due to each drying test is obtained. Head yield drop due to drying in Table 4.16 shows an interesting trend. The average head yield drops in the three passes are 0.7 % for the first pass, 2.4 % for the second pass, and 0.6 % for the third pass.

Kunze and Calderwood (1980) theorized the existence of a critical moisture content between 14 and 26 %, above which the grain is plastic enough to resist fissuring due to moisture stress. Below this critical moisture content, rapid adsorption of moisture by the grain fissures the kernels. Bhattacharya and Swamy (1967) found this critical moisture content to be around 16 to 17 %, in their experiments on parboiled rice. The higher drop in head yield in the second pass compared to the first and the third passes can be explained by this theory.

The 2.4 % head yield drop due to drying is within the acceptable limit of the stringent requirement of the U.S. rice industry. From these tests, the three-stage concurrentflow dryer demonstrated its ability to maintain acceptable head yields when drying rice.

4.2.2 Simulation

The Michigan State University concurrentflow dryer simulation model is used to simulate the drying of medium-grain rice under California conditions. The experimental results are compared with the simulated results in order to validate the model.

Three typical drying passes, in drying rice from approximately 23 % to 13.5 %, are simulated. In the actual experiment, these passes correspond to tests 1, 6, and 11, as shown in Table 4.13.

The average drying conditions for experimental tests 1, 6, and 11 are the inputs to the simulated drying passes 1, 2, and 3. These drying conditions are tabulated in Table 4.17. The dryer lengths, the tempering lengths, and the airflow rates of the three drying stages are also given in Table 4.18.

Table 4.17 Common inputs of the simulation and experimental drying passes in the concurrentflow dryer.

Drying Pass[a]	Ambient Temp. (°C)	Ambient R.H. (%)	Inlet Grain Temp. (°C)	Inlet Grain M.C. (% w.b.)	Inlet Drying Air Temp. (°C)			Grain-flow Rate (t/h/m²)
					Top	Mid	Bot	
1	16.1	33	24.4	23.5	124.4	96.1	77.8	3.467
2	17.8	37	33.3	20.4	107.8	87.8	81.1	3.373
3	17.2	38	35.6	17.4	81.1	65.0	66.1	3.281

[a] Typical three drying passes in drying rice from about 23 % to about 13.5 %.

Table 4.18 Constant pressures, airflows, and dimensions in all drying passes in the concurrentflow dryer.

Stage	Top	Middle	Bottom
Static Pressure (kPa)	2.5	3.0	3.5
Airflow Rate ($m^3/min/m^2$)	40.2	37.0	37.9
Dryer Length (m)	0.85	1.16	1.31
Tempering Length (m)	5.2	5.2	1.7

Table 4.19 Comparison of the experimental and simulated results of drying medium-grain rice in a concurrentflow dryer.

Drying Pass[a]	Outlet Grain Moisture (% w.b.)		Outlet Grain Temperature (°C)		Energy Efficiency (kJ/kg H_2O)	
	Exp	Sim	Exp	Sim	Exp	Sim
1	19.2	20.1	34.4	32.9	3225	3270
2	16.5	16.9	37.8	36.1	3802	3622
3	14.1	14.8	37.2	34.4	4795	4221

[a] Drying conditions, see tables 4.17 and 4.18.

Table 4.20 Comparison of the experimental and simulated tempering temperatures of the concurrentflow dryer while drying medium-grain rice.

Drying Pass[a]	Top (°C)		Middle (°C)		Bottom (°C)	
	Exp	Sim	Exp	Sim	Exp	Sim
1	38.9	35.0	37.8	34.8	33.9	32.9
2	38.9	38.2	39.4	36.9	37.8	36.1
3	38.3	37.3	37.8	34.8	37.8	34.4

[a] Drying conditions, see tables 4.17 and 4.18.

4.2.2.1 Comparison of Simulated and Experimental Results

Table 4.19 compares the grain moisture content, the grain temperature, and the energy efficiency after each drying pass. The average final (outlet) rice moisture contents of the experimental passes 1, 2, and 3 are 19.2, 16.5, and 14.1 % respectively, while those of the simulation are 20.1, 16.9, and 14.8 %. Although the simulated outlet grain moisture contents are slightly higher than the experimental values, the agreement appears to be excellent. In simulating the drying of biological products, trends are more important because it is impossible to be exact due to the variability in the product and the constantly changing ambient conditions.

Grain temperature is particularly important in the drying of rice because of its effect on kernel checking. The experimental and simulated tempering temperatures are compared in Table 4.20. All the simulated values are lower than the corresponding experimental values. It is not clear why this is the case. The largest difference is for the top stage of pass 1, where the average experimental tempering temperature is 38.9°C while the simulated value is 35.0°C. The smallest difference is for the top stage of pass 2, where the experimental value is 38.9°C and that of the simulation is 38.2°C. The simulated tempering temperatures are therefore 0.7 to 3.9°C lower than the experimental data. However, the trends in the rise and fall of the tempering temperatures from one stage to the next, and from one pass to the next, are consistent.

The energy efficiency comparison between the experimental and the simulated runs is given in Table 4.19. The experimental data show an increase in the energy requirement from 3,225 kJ/kg H_2O in pass 1 to 4,795 kJ/kg H_2O in pass 3 while the simulated values increase from 3,270 to 4,390 kJ/kg H_2O. In the first pass, the simulated energy requirement is 1.4 % higher than the experimental value. The experimental value is higher by 4.7 % in the second pass, and again higher in the third pass by 12 %. Thus, there is close agreement in the energy efficiencies of the simulated and the experimental drying passes.

4.2.2.2 Validation of the Concurrentflow Drying Model

The outlet moisture contents of the simulated and the experimental drying passes compare closely. On the whole, the outlet grain temperatures and the tempering temperatures in the simulated cases are only moderately lower than the corresponding values of the experimental runs. Also, the energy efficiencies of the simulated and the experimental drying passes vary by less than 12 % in all cases. From this information, it is concluded that the Michigan State University concurrentflow drying model satisfactorily simulates the drying of rice in a three-stage concurrentflow dryer.

4.3 Simulation of Rice Drying in Malaysia

The Michigan State University in-bin counterflow and concurrentflow drying models are used to simulate the drying of rice under Malaysian conditions. The average ambient temperature in Malaysia is 29.4°C; the average relative humidity is 85 %. Tables 4.21 and 4.22 tabulate the ambient and drying conditions.

Rice at 23 % is dried down to 13.5 % in three passes with 12-24 hours of tempering between passes. This is a common practice among rice dryer operators in trying to minimize thermal and moisture stresses in the kernels, and hence minimize head-yield loss. Usually, the rice is dried from 23 to 19 % in the first pass, 19 to 16 % in the second pass, and from 16 to 13.5 % in the third pass. It is assumed that the 13.5 % moisture rice is aerated for cooling, reducing the moisture content by 0.5 %, and thus bringing the rice to the safe-storage moisture content of about 13 %. It is also assumed that there is no loss of moisture from the rice during tempering.

Based on the author's experience and communications with personnel in the rice-drying industry, in order to maintain the head-yield loss due to drying below 3 %, the temperature of the rice leaving the dryer should not exceed 46°C in the first pass, 41°C in the second pass, and 35°C in the third pass. To maintain these rice temperatures, the in-bin counterflow dryer air temperature is kept at about 47°C in the first pass, 41°C in the second pass, and 35°C in the third pass. The air temperatures in the concurrentflow dryer are about 127, 121, and 121°C for the first, second, and third stages of the first pass. In the second pass, the air temperatures are about 104, 77, and 66°C for the first, second, and third stages, respectively. Air temperatures of about 99, 54, and 34°C are maintained in the final pass.

The drying capacity or the average grain flow of the in-bin counterflow dryer is dependent on the initial moisture content, the drying-air temperature, the airflow rate and the rice moisture content at which the sweep auger is activated. With a constant rice depth of 1.4 m maintained in the drying bin, the static pressure is constant at 0.96 kPa, resulting in a steady airflow rate of 12.1 $m^3/min/m^2$. At the specified inlet and outlet rice moisture contents for the different passes, and the above airflow rate and air temperatures, the average grain flow rate was found to be 0.18 m/h in the first pass, 0.19 m/h in the second pass, and 0.07 m/h in the third pass.

The concurrentflow dryer allows the independent selection of the airflow rates, the air temperatures and the grain flow rate for each of the three stages. The problem of the changing rice bulk density in the drying bed is solved in the simulation by using a constant dry-matter flow rate through the dryer. In order to match the requirements of removing a specified amount of moisture in the different passes, and maintaining the desired outlet grain temperatures, the drying-air temperatures along with the airflow rates and the dry matter flow rates were adjusted by trial and error in the different stages. The resulting airflow rates and static pressures in the various stages and the various passes of the concurrentflow dryer are given in Table 4.22. The average grain flow rates under these conditions are 6.5 m/h in the first pass, 6.32 m/h in the second pass, and 4.51 m/h in the third pass (see Table 4.21).

The inlet and outlet rice temperatures, the inlet and outlet rice moisture contents and the dry and wet weight capacities of the in-bin counterflow and the concurrentflow dryers, operating under Malaysian conditions, are listed in Table 4.23. The energy efficiencies of both drying systems are also given in Table 4.23.

The wet weight capacity of the 12′x 12′ concurrent flow dryer is about 29 times that of the 18′ diameter in-bin counterflow dryer in the first pass. In the second and third passes, the capacities of the concurrentflow dryer are about 28 and 56 times that of the in-bin counterflow dryer, respectively. These large differences in capacities are due to the much higher drying temperatures used by the concurrentflow dryer. Further, the three-stage concurrentflow

Table 4.21 Ambient and drying conditions for simulating the in-bin counterflow and the concurrentflow dryers in Malaysia.

Dryer[a] (Pass)	Ambient Temp. (°C)	Ambient R.H. (%)	Av. Grain Flow (m/h)	Drying[b] Air Temp. (°C)
IBCF(1)	29.4	85	0.18	47.2
CCF(1)	29.4	85	6.50	126.7 121.1 121.1
IBCF(2)	29.4	85	0.19	41.1
CCF(2)	29.4	85	6.32	104.4 76.7 65.6
IBCF(3)	29.4	85	0.07	35.3
CCF(3)	29.4	85	4.51	98.9 54.4 34.4

[a] IBCF(1) refers to the first pass of the in-bin counterflow dryer while CCF(3) refers to the third pass of the concurrentflow dryer.

[b] The three values for the concurrentflow dryer correspond to the top, middle, and bottom stages of the dryer.

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Table 4.22 Static pressures and airflow rates for simulating the in-bin counterflow and the concurrentflow dryers in Malaysia.

Dryer[a] (Pass)	Static Pressure[b] (kPa)			Airflow Rate[b] ($m^3/min/m^2$)		
IBCF(1)		0.96			12.1	
CCF(1)	2.09	2.34	2.93	39.6	33.5	36.6
IBCF(2)		0.96			12.1	
CCF(2)	2.09	2.59	2.93	39.6	36.6	36.6
IBCF(3)		0.96			12.1	
CCF(3)	2.09	2.83	3.49	39.6	39.6	42.7

[a] Refer to Table 4.21 footnote [a].

[b] Refer to Table 4.21 footnote [b].

Table 4.23 Comparison of the simulated performances of the 18′ diameter in-bin counterflow and the three-stage 12′x 12′ concurrentflow dryers under Malaysian conditions.

Dryer[a] (Pass)	Inlet Rice Temp. (°C)	Outlet Rice Temp. (°C)	Inlet Rice M.C. (% w.b.)	Outlet Rice M.C. (% w.b.	Dry Weight Capacity (kg/m²/h)	Wet Weight Dryer Capacity (t/m²/h)	Energy Efficiency (kJ/kg H_2O)
IBCF(1)	29.4	46.1	23.0	18.9	89	0.1153	7,439
CCF(1)	29.4	43.6	23.0	19.0	2,598	3.3738	3,216
IBCF(2)	43.3	40.4	18.9	15.9	96	0.1182	2,596
CCF(2)	40.8	38.2	19.0	16.0	2,657	3.2805	3,285
IBCF(3)	37.8	35.2	15.9	13.5	35	0.0418	2,826
CCF(3)	35.6	35.1	16.0	13.6	1,969	2.3436	5,801

[a] Refer to Table 4.21 footnote [a].

dryer has three drying stages, the in-bin counterflow dryer has only one.

The simulation results provide the drying capacity for each drying pass. For the physical and the economical analysis of rice-drying systems, the overall drying capacity of each dryer, in drying rice from 23 to 13.5 % moisture, is needed. The overall capacity is determined by considering 1 tonne of rice at 23 % moisture content, and drying it in 3 passes to 13.5 %. In the first pass, the time taken to dry the tonne of rice to 19 % moisture is calculated from the first pass drying capacity. In the second pass, 0.95 tonne (1 - moisture removed in the first pass) is dried to 16 % moisture content. The time taken for drying is derived from the drying capacity of the second pass. Similarly, in the third pass, 0.917 tonne (0.95 - moisture removed in the second pass) is dried to 13.5 % moisture content, and the drying time is derived from the drying capacity of the third pass. The reciprocal of the total time required for the three passes is the overall drying capacity. The overall drying capacity of the 12′x 12′ three-stage concurrentflow dryer is 13.69 tonnes per hour (see Table 4.25). The overall drying capacity of the 18′ in-bin counterflow dryer is 0.612 tonne per hour.

The data on the energy efficiencies show that in the first pass, 2.3 times as much energy is required by the in-bin counterflow dryer to dry a unit weight of moisture than in the concurrentflow dryer (i.e. 7,439 kJ/kg vs 3,216 kJ/kg).

In the second pass, the in-bin counterflow dryer is more energy efficient, requiring only 2,596 kJ/kg moisture compared to 3,285 kJ/kg moisture for the concurrentflow dryer. The in-bin counterflow dryer requires about half the energy required by the concurrentflow dryer in the third pass (i.e. 2,826 kJ/kg vs 5,801 kJ/kg).

For the physical and the economical analysis of rice-drying systems, the overall energy efficiencies are needed. As in the case of the overall capacity, consider the drying of 1 tonne of rice at 23 % moisture content in 3 passes to 13.5 %. In each pass, the product of the moisture removed and the energy efficiency is the total energy used in that pass. The sum of the total energy of the 3 passes is the overall energy required to dry 1 tonne of rice from 23 to 13.5 % moisture content. The overall energy efficiency of the 12′x 12′ three-stage concurrentflow dryer is 3,861 kJ/kg moisture (see Table 4.25). The overall energy efficiency of the 18′ in-bin counterflow dryer is 6,408 kJ/kg moisture.

4.4 Economic Analysis

The perennial problem of the Malaysian rice industry has been the lack of drying capacity at the LPN (National Rice Board) rice drying and milling complexes, especially during the harvesting of rice in the wet season. While the private and cooperative rice mills stop purchasing rice when its drying capacity has been reached, the government's LPN rice complexes cannot for political reasons. One of the main objectives of setting up the government mills is to protect the poorer rice farmers. When a LPN complex is overloaded with incoming rice, excess rice is shipped at a loss to private or coop complexes. However, during a bumper harvest, or when the harvested rice is very wet, all the mills in Malaysia are overloaded with too much wet rice. Thus, heavy losses occur due to grain spoilage.

The main reason for not expanding the LPN complexes' drying capacities is the high cost of the drying system. The mills use high-capacity mixed-flow dryers purchased with international loans. The cost is, under the present economic conditions, prohibitive to expand the drying capacities. Inexpensive makeshift drying systems are used to salvage the excess wet rice. Thus, sacks of rice are arranged to form tunnels, each with one closed end; heated air from portable burner/blower is blown through the tunnels. Some drying occurs, but spoilage remains high due to the inadequacy of such a system (Driscoll and Adamczak 1987).

The concurrentflow (CCF) and the in-bin counterflow (IBCF) dryers are not at present employed in Malaysia (a CCF dryer is operating successfully in neighboring Thailand, several IBCF dryers are operating on an experimental basis in the Southern U.S.). Data from the experimental tests, and simulated data run under Malaysian conditions, are the basis for proposing eight alternative drying systems for use in Malaysia. A capital investment model developed by Harsh (1972), and which utilizes capital budgeting (life cycle costing) is used to analyze the economics of the proposed CCF and IBCF drying systems.

4.4.1 The Drying Problem

Consider a rice production area of 3000 ha in Malaysia producing 2.47 wet tonnes/ha (Fredericks and Wells 1983) or approximately 15,420 metric tonnes a year over two growing seasons (see Table 4.24). Each harvesting season lasts 30 days. The rice is dried at LPN complexes or private rice mills. The 1990 cost of drying at these facilities is US$20.95 per tonne of wet rice (Ibrahim 1990). One or more drying facilities may be set up to service the 3,000 ha production area. Assuming a steady daily rate of harvest, and dividing the total production by the number harvesting days per year, yields the daily rice output of 257 wet tonnes. This production rate is valid because the planting dates are staggered in Malaysia in order to facilitate contract-harvesting by custom-combine owners.

Table 4.24 Rice-drying conditions in Malaysia.

Total farm area served (ha)	3,000
Average yield of long-grain rice (wet t/ha)	2.47
Number of growing seasons per year	2
Number of harvesting days per season	30
Total rice harvested per year (wet t)	15,420
Expected daily volume of drying (wet t/day)	257
Average dry-bulb temperature (°C)	29.4
Average relative humidity (%)	85

Table 4.25 Operating conditions in Malaysia of several drying systems.

Dryer[a]	CCF12	IBCF18	IBCF24	IBCF36
Overall capacity ($t/h/m^2$)	1.023	0.026	0.026	0.026
Capacity (t/h/dryer)	13.68	0.612	1.088	2.448
Number of dryers	1	20	12	5
Drying hours/day/dryer	18.78	21.00	19.68	21.00
Total drying hours/day	18.78	419.93	236.21	104.98
Overall Energy Efficiency[b] (kJ/kg H_2O)	3,861	6,408	6,408	6,408
Fuel/t rice (L LPG)	15.85	19.82	19.82	19.82

[a] CCF12 is the 12′x 12′ concurrentflow dryer
IBCF18, IBCF24, and IBCF36 are in-bin counterflow dryers with 18′, 24′, and 36′ bin diameters, respectively.

4.4.2 Proposed Drying Systems

The simulation runs of the in-bin counterflow and the concurrentflow dryers, drying rice under Malaysian conditions, yield the drying capacities and the fuel efficiencies of the two dryers. From the dryer capacities and the expected daily rice harvest, the number of dryers and daily operating hours are calculated. The fuel usage of each dryer is determined from its energy efficiency, the fuel heating value of LP-gas, and the moisture removed from the rice. Liquified propane gas has a heating value of 26,756 kJ/L.

Table 4.25 shows the operating conditions of the different dryer systems. Using a 12′x 12′ (3.66 x 3.66m) concurrentflow dryer, the total operating hours per day is 18.78; only one dryer is needed. Choosing an 18′ (5.49m) diameter in-bin counterflow dryer with a drying capacity of 0.612 tonne per hour, requires 20 dryers, each operating 21 hours a day. (Daily drying hours should not exceed 21-22 hours because time is required for maintenance and repairs.) Using a larger 24′ (7.32m) diameter in-bin counterflow dryer, requires only 12 dryers each running 19.68 hours daily. The number of dryers used can be further reduced to 5 by employing 36′ (10.97m) diameter IBCF dryers, each operating 21 hours a day.

Obviously, the single concurrentflow dryer has to be located at one drying site. The multiple dryers of the in-bin counterflow drying system allow the flexibility of locating all the dryers in one location, or one to several in multiple locations. Placing the dryers in multiple strategic locations of the region reduces transport time, energy usage, and vehicle and equipment use. Also, the smaller IBCF dryer can dry smaller lots. However, the initial investment and operating costs are normally higher.

Eight rice drying systems are considered for the Malaysian situation. The first system consists of a single concurrentflow dryer located at one location. This system is abbreviated as CCF12/1, where "12" refers to the size of the dryer and "1" refers to one location. Another system consists of placing five 36′ in-bin counterflow dryers at a single drying facility. The next option is to place each at a separate location. Their abbreviated references are IBCF36/1 and IBCF36/5. Similarly, the 24′ in-bin counterflow dryers are located together and separately as IBCF24/1 and IBCF24/12. Finally, the twenty 18′ in-bin counterflow dryers are placed at one location, singly in 20 different locations, and in pairs at 10 different sites; they are referred to as IBCF18/1, IBCF18/20, and IBCF18/10, respectively.

In Malaysia, wet rice is transported in gunny sacks to the drying facility; dry rice is stored in sacks and in silos. In order to make a realistic comparison among the eight drying systems, similar operating conditions are assumed. The rice is dried from 23 to 13.5 % in three passes, 23-19 %, 19-16 %, and 16-13.5 % with 12-24 hours of tempering between passes.

The multi-pass drying and the necessary tempering necessitate the availability of tempering bins. Two tempering bins with adequate capacities are needed at each drying facility. Locating the dryers at separate sites requires more tempering bins, increasing the investment.

4.4.2.1 Single-site Concurrentflow Drying System

The CCF12/1 system employs a high capacity (13.69 t/h) three-stage concurrentflow dryer. Like other single-site drying systems, it requires two large tempering bins. Two 10.97m diameter bins with perforated floors, aeration fans, and unloading augers are used for tempering. The bins are filled to 2.4m depth during tempering.

The three-stage concurrentflow dryer, measuring 3.66m x 3.66m in cross-section and 35m in height, requires about 160 t of rice to fill up. The dryer has to start full. On the first day of the season, the 257 t of 23 % moisture rice received is predried with air slightly above ambient temperature. On the second day, the first-day rice is dried to 19 %. Two passes are possible on the third day, 19 to 16 % and 23 to 19 %. From the fourth day on, three passes are carried out.

Drying with the concurrentflow dryer requires careful monitoring of the flow of rice batches, knowing when to start, to turn up, and to turn off the burners as the various rice batches pass certain points in the dryer. To assist the operator, a controller has been developed to automate this process (Moreira 1989).

Wet rice is stored in a wet holding bin and is conveyed by an elevator to the top of the dryer. A permanent conveying system is needed to transfer dried rice from the dryer to the tempering bins and vice versa.

The operating conditions of the CCF12/1 system are tabulated in Table 4.21. During the first drying pass, the drying air temperatures are 126.7, 121.1, and 121.1°C in the first, second and third stages, respectively. During the second pass, lower drying air temperatures of 104.4, 76.6, and 65.5°C are used in the first, second, and third stages, respectively. In the final pass, the air temperatures of the first , second and third stages are 98.9, 54.4, and 34.4°C, respectively.

4.4.2.2 Single-site In-bin Counterflow Drying Systems

The IBCF36/1 drying system consists of five 10.97 m in-bin counterflow dryers located in a circle around a dump pit (Figure 4.1) The five dryers are connected by horizontal transfer augers such that rice from the first dryer can be diverted to the second dryer and so on to the last dryer. During drying, the rice depths in the dryers are continuously

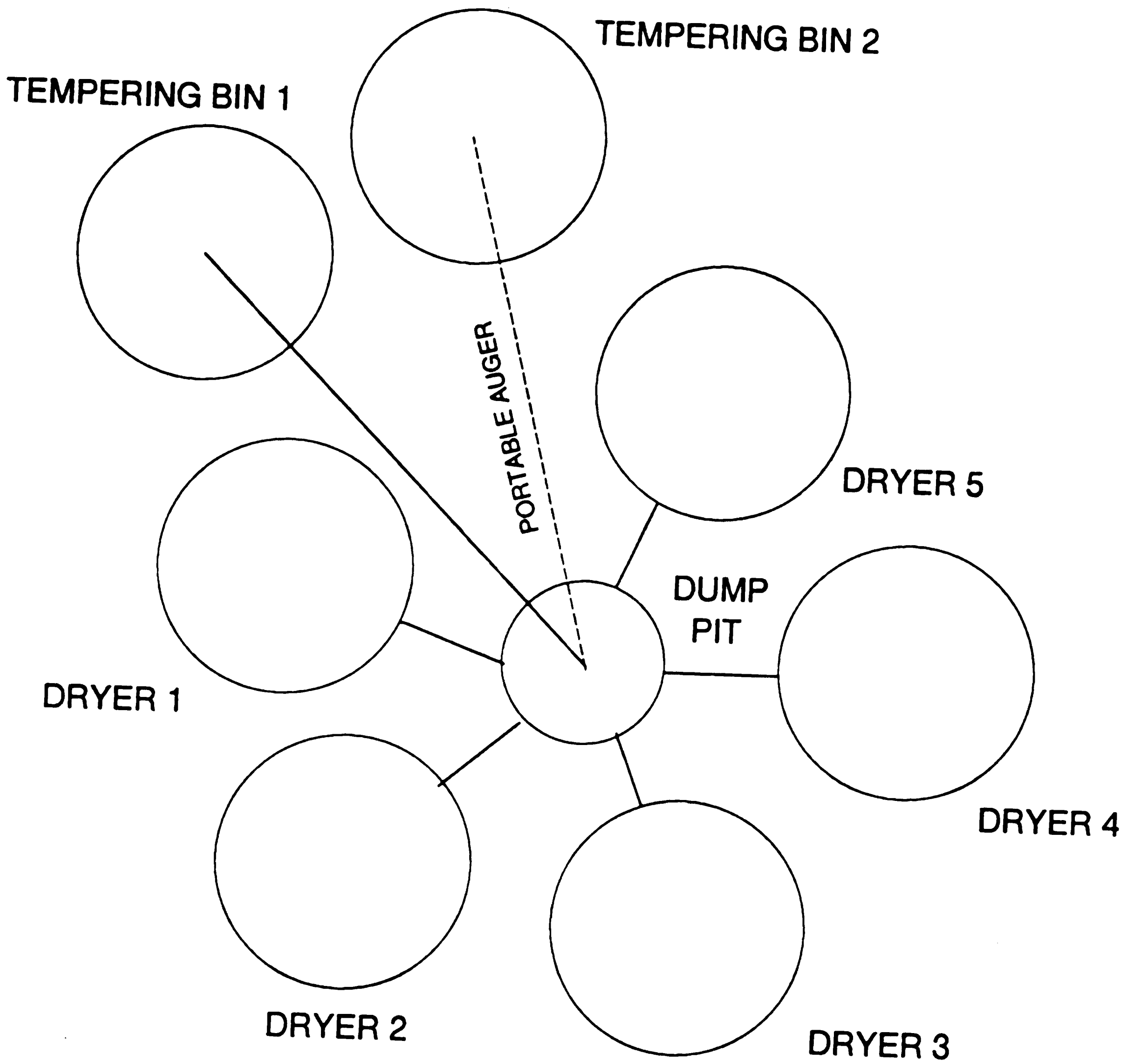

Figure 4.1 Drying system IBCF36/1

monitored to maintain them at about 1.4 m (Marks et al. 1988), the optimum depth for IBCF drying. Dried layers are removed by the tapered sweep auger and conveyed by the transfer auger to the dump pit. A second auger transfers the dried rice from the dump pit to the tempering bin. The tempering bins at all single-site facilities are similar, 10.97 meter in diameter.

The management of the in-bin counterflow dryers is simple. Rice received on the first day of the season is dried from 23 to 19 %, and is stored for 12-24 hours in the tempering bin. On the second day, the 19 % rice is dried to 16 %; subsequently, the newly-received rice of 23% moisture is dried to 19 %. From the third day, the three passes are run until the end of the drying season. Dried rice from the last pass is transferred in sacks to the storage facilities.

The IBCF24/1 and the IBCF18/1 systems are similar to the IBCF36/1, system except the dryers are smaller and hence more numerous. The twelve dryers of the IBCF24/1 are arranged in two circles of six dryers, each surrounding a dump pit. Two augers are needed to fill the dryers, and another two to fill the tempering bins.

The IBCF18/1 has twenty dryers forming three circles circling three dump pits. Six augers are needed.

The outlet grain temperature of the in-bin counterflow dryer approaches the drying-air temperature. Therefore, the temperatures of the drying air are set at about 46°C for the first pass, 41°C for the second pass and 35°C for the last pass.

The operating conditions of the IBCF systems are tabulated in Table 4.21 and Table 4.22, and are described in section 4.5.

4.4.2.3 Multiple-site In-bin Counterflow Drying Systems

The IBCF36/5, IBCF24/12, and IBCF18/20 systems operate one in-bin counterflow dryer at each of several scattered drying centers (Figure 4.2). A pair of dryers operate in each of the ten drying centers of the IBCF18/10 system. There are two tempering bins at each drying center,each with a diameter of 5.49 m. No dump pits or special arrangement of the dryer(s) and the tempering bins are necessary.

The operating conditions are similar to those of the IBCF36/1 system.

4.4.3 Inputs to the Capital-Investment Program

Summaries of the cost of the various drying/system-components in Malaysia are tabulated in Tables 4.26 and 4.27. The cost of the dryer for the CCF12/1 system is $307,000. Five 36′ in-bin counterflow dryers are needed for the IBCF36/1 system to match the capacity of the CCF12/1 system; the cost of the five dryers, $161,675, is about half that of the concurrentflow drying system. At the same capacity the total

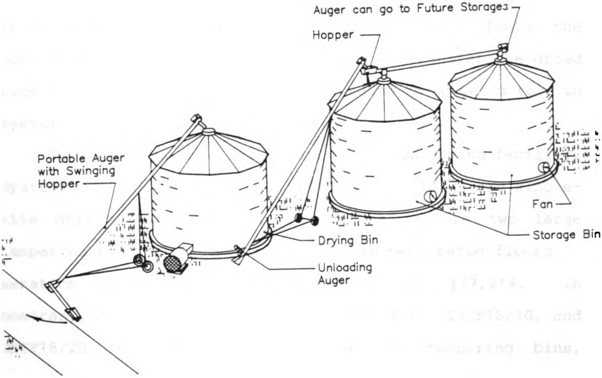

Figure 4.2 Drying system IBCF18/20 (Midwest Plan Service 1988).

dryer cost increases as the number of dryers increases. The total cost of twelve 24′ dryers in the IBCF24/1 system is $249,780.

Although twenty 18′ in-bin counterflow dryers are needed for each of the IBCF18/1, IBCF18/10, and IBCF18/20 systems, the total dryer cost for the IBCF18/1 is $367,900 and is thus lower than that of the other two at $423,800. This is because a less expensive dryer model is required when the dried rice is conveyed into a dump pit in system IBCF18/1. [note: the more expensive dryer model is required to transfer the dried rice directly to the tempering bin through the dryer′s roof in systems IBCF18/10 and IBCF18/20.]

Two tempering bins are required at each drying facility. Systems CCF12/1, IBCF16/1, IBCF24/1, and IBCF18/1 are single-site drying facilities, and therefore require two large tempering bins each. Two 36′ bins with perforated floors, aeration fans, and unloading augers cost $27,214. In contrast, drying systems IBCF36/5, IBCF24/12, IBCF18/10, and IBCF18/20 require 10, 24, 20, and 40 tempering bins, respectively. With the smaller capacity at each drying site, the smallest available bins (18′) are used. The total cost of the tempering bins for the drying systems IBCF36/5, IBCF24/12, IBCF18/10, and IBCF18/20 are $53,470, $116,544, $97,120, and 194,240, respectively. These represent 15 to 20 % of the total cost of the system; while for the CCF and the IBCF one-site systems this amounts to only 7 % to 17 %.

Table 4.26 Estimated 1990 costs of four single-site rice drying centers in Malaysia.

Drying system[a]	CCF12/1	IBCF36/1	IBCF24/1	IBCF18/1
Dryer(s) ($)	307,000	161,675	249,780	367,900
Tempering bins[b] ($)	27,214	27,214	27,214	27,214
Add. conveying system ($)	1,200	10,224	21,950	31,259
Equipment subtotal ($)	335,414	199,113	298,944	426,373
Freight, insurance, duty ($)	83,854	49,778	74,736	106,593
Concrete ($)	4,800	16,800	17,640	16,800
Installation ($)	130,000	14,000	32,000	24,000
Miscellaneous ($)	6,708	3,982	5,979	8,527
Total drying system cost ($)	560,776	283,674	429,299	582,294

[a] *CCF12/1, IBCF36/1, IBCF24/1, and IBCF18/1 refer to drying systems with simalar capacities containing one 12′x 12′ concurrentflow dryer, five 36′ diameter in-bin counterflow dryers, twelve 24′ diameter in-bin counterflow dryers, or twenty 18′ diameter in-bin counterflow dryers, each system sited at a single location.*

[b] *Two tempering bins of 10.97m diameter.*

Table 4.27 Estimated 1990 costs of four multiple-site rice drying centers in Malaysia.

Drying system[a]	IBCF36/5	IBCF24/12	IBCF18/10	IBCF18/20
Dryer(s) ($)	178,040	285,096	423,800	423,800
Tempering bins[b] ($)	53,470	116,544	97,120	194,240
Add. conveying system ($)	12,635	30,324	38,540	50,540
Equipment subtotal ($)	244,145	431,964	559,460	668,580
Freight, insurance, duty ($)	61,036	107,991	139,865	167,145
Concrete ($)	18,000	27,240	24,000	36,000
Installation ($)	20,000	42,000	40,000	60,000
Miscellaneous ($)	4,883	8,639	11,189	13,372
Total drying system cost ($)	348,064	617,834	774,514	945,097

[a] *IBCF36/5, IBCF24/12, IBCF18/10, and IBCF18/20 refer to drying systems with simalar capacities containing five 36′ diameter in-bin counterflow dryers, twelve 24′ diameter in-bin counterflow dryers, or twenty 18′ diameter in-bin counterflow dryers.*

Every dryer of drying systems IBCF36/5, IBCF24/12, and IBCF18/20 is located at a different site.

Every two dryers of the IBCF18/10 system is located at a different site.

[b] *Number of 5.49m diameter tempering bins: 10, 24, 20, 40, respectively.*

Table 4.28 Inputs to the life-cycle costing program for the economic analysis of four single-site rice drying centers under Malaysian conditions.

Drying system[a]	CCF12/1	IBCF36/1	IBCF24/1	IBCF18/1
Annual rate of drying (tonne/yr)	15,420	15,420	15,420	15,420
Malaysian drying cost ($/tonne)	20.95	20.95	20.95	20.95
Total cost of drying system ($)	560,776	283,674	429,299	582,294
Drying system lifetime (yr)	10	10	10	10
Depreciation method	Strt. line	Strt. line	Strt. line	Strt. line
Percent of total cost borrowed (%)	100	100	100	100
Repayment period of loan (yr)	10	10	10	10
Interest rate on loan (%)	10	10	10	10
Income tax bracket (%)	30	30	30	30
Equipment repair cost ($)	16,771	9,956	14,947	21,319
Energy cost per hour ($/h)	47.56	53.19	56.73	53.19
Labor cost per hour ($/h)	11	13	15	18
Drying capacity (tonne/h)	13.69	12.24	13.06	12.24
Inflation rate of purchase cost (%)	4.0	4.0	4.0	4.0
Inflation rate of energy cost (%)	1.9	1.9	1.9	1.9
Inflation rate of labor cost (%)	6.0	6.0	6.0	6.0

[a] Refer to Table 4.26 footnote [a].

Table 4.29 *Inputs to the life-cycle costing program for the economic analysis of four multiple-site rice drying centers under Malaysian conditions.*

Drying system[a]	*IBCF36/5*	*IBCF24/12*	*IBCF18/10*	*IBCF18/20*
Annual rate of drying (tonne/yr)	15,420	15,420	15,420	15,420
Malaysian drying cost ($/tonne)	20.95	20.95	20.95	20.95
Total cost of drying system ($)	348,064	617,834	774,514	945,097
Drying system lifetime (yr)	10	10	10	10
Depreciation method	Strt. line	Strt. line	Strt. line	Strt. line
Percent of total cost borrowed (%)	100	100	100	100
Repayment period of loan (yr)	10	10	10	10
Interest rate on loan (%)	10	10	10	10
Income tax bracket (%)	30	30	30	30
Equipment repair cost ($)	12,207	21,598	27,973	33,429
Energy cost per hour ($/h)	53.19	56.73	53.19	53.19
Labor cost per hour ($/h)	26	52.5	44.5	45
Drying capacity (tonne/h)	12.24	13.06	12.24	12.24
Inflation rate of purchase cost (%)	4.0	4.0	4.0	4.0
Inflation rate of energy cost (%)	1.9	1.9	1.9	1.9
Inflation rate of labor cost (%)	6.0	6.0	6.0	6.0

[a] *Refer to Table 4.27 footnote [a].*

The conveyor required for the CCF12/1 drying facility is for transferring rice from the dryer to the tempering bins. Thus, the cost of additional conveyor for the CCF12/1 system is only $1,200. The IBCF systems, depending on their dryers and tempering bins arrangements require conveying systems ranging in cost from $10,224 for system IBCF36/1 to $50,540 for system IBCF18/20.

The equipment subtotals in Tables 4.26 and 4.27 show that the IBCF36/1 drying system has the lowest cost at $199,113, and the IBCF18/20 has the highest cost at $668,580. Under present Malaysian conditions, the import duty, freight, and insurance charges are 25 % of the equipment cost.

The amount of concrete needed for each drying system depends on the floor area of the dryers and the tempering bins. The IBCF18/20 system, with the largest number of dryers and tempering bins, requires the most concrete, costing $36,000; the CCF12/1 requires the least at $4,800.

The CCF12/1 drying system requires the largest erection cost, $130,000. The IBCF18/20 system is next highest in installation cost, $60,000. The lowest installation cost of $14,000 is for the IBCF36/1 system.

A miscellaneous cost is added to pay for unexpected minor equipment- and installation-requirements. The contingency cost is estimated to be 2 % of the equipment cost.

The total drying cost shows that the IBCF36/1 and IBCF36/5 systems have the lowest costs at $283,674 and

$348,064, respectively. The most costly drying system has the smallest drying capacity per dryer, and is dispersed over the largest number of sites (i.e. IBCF18/20 at $945,097). Systems IBCF36/1, IBCF24/1, and IBCF18/1 are cheaper than systems IBCF36/5, IBCF24/12, and IBCF18/20, respectively. This shows that a centrally-located drying facility is less costly than a decentralized system. However, transport charges from the field to the centralized drying facility are higher than for a decentralized drying facility. Other factors such as grain spillage, grain spoilage, cost of purchasing, etc. should be considered in a follow-up study to make a more realistic comparison (Ryland 1986).

Tables 4.28 and 4.29 list the other input data to the capital budgeting program. The principal yardstick for evaluating the economics of the proposed drying systems is the cost of drying rice in Malaysia. Ghaffar and Hassan (1987) found the cost of drying rice in Malaysia in 1987 ranged from $14.35 to $15.60 per tonne. Ibrahim (1990) stated that the charge for rice drying in Malaysia in June 1990 was $20.95 per tonne; this is used in this analysis.

The repair costs are based on the total costs of the dryers. The moving parts in a dryer include the fans, conveyors, and the grain spreader. It is estimated that the maintenance plus repair costs for a dryer over the 10 to 11 years of dryer operation are 5 % of the cost of the dryer. System IBCF36/1 has the lowest estimated repair cost of $9,956 while system IBCF18/20 has the highest estimated repair cost at $33,429.

The labor required in each drying facility depends on the man-hours required for each task. For the CCF12/1 drying system, two men are required to monitor the dryer at all times. Three men are needed to weigh, sample, and determine the quality of in-coming rice; each will work half the day. Emptying sacks of wet rice into the elevator hopper and filling the sacks with dried rice requires five men during the operation of the dryer. Repair and maintenance is estimated to require two men, each working half a day. One man is constantly needed to drive the tractor/loader, to carry rice sacks and to clean the yard. Finally, a manager is needed requiring half of his time to supervise the operation of the dryers. Adding the man-hours needed per day, and dividing the total man-hours by the total hours the dryer is operating, results in eleven man-hours required per hour of dryer operation. At $1 per hour labor cost in Malaysia, the total labor cost per hour of dryer operation is $11.

Similar labor-requirement calculations are made for the other drying systems. However, for the multiple-site systems, labor is not efficiently utilized because it will take more than one person to run the drying facility, no matter how small, because some tasks must be performed simultaneously. The smallest labor cost per hour of dryer operation is $11 for the CCF12/1 system; the highest labor cost is $52.5 for the

IBCF24/12 system.

The drying systems are purchased with 100 % borrowed capital. The current bank interest rate in Malaysia is 10% per annum. It is assumed that the equipment life is 10 years due to technical obsolescence. The straight-line depreciation method is used in the computations. The present inflation rates of the purchase cost, the energy cost and the labor cost in Malaysia are 4.0, 1.9, and 6.0, respectively. The owner of the drying facility is assumed to be in the 30 % income tax bracket.

4.4.4 Economic Comparison of the Drying Systems

The results of the capital-investment program (capital budgeting) are tabulated in Tables 4.30 to 4.32. Tables 4.30 and 4.31 list the total costs and savings of owning and operating the drying centers for 11 years compared to paying for custom-drying. Tables 4.32 and D.1 to D.7 in Appendix D show the yearly cash flows of the individual drying systems over eleven year periods.

The breakeven return ranges from $8.81/tonne for the IBCF36/1 system to $17.56/tonne for the IBCF18/20 system. Since the 1990 cost of drying rice in Malaysia is $20.95, all the analyzed drying systems are economical. Furthermore, positive cash flows occur for each system during each of the 11 years considered.

Table 4.30 ***A comparison of total costs and savings of four single-site rice drying centers after operating for 11 years in Malaysia.***

Drying system[a]	CCF12/1	IBCF36/1	IBCF24/1	IBCF18/1
Breakeven return ($/t)	9.96	8.81	10.19	11.94
Ownership cost (%)	48.7	27.8	36.4	42.2
Before-tax savings ($)	4,074,303	4,074,303	4,074,303	4,074,303
Before-tax expenses ($)	1,377,948	1,431,324	1,554,318	1,745,273
Before-tax net savings ($)	2,696,355	2,642,979	2,519,985	2,329,030
After-tax net savings ($)	1,887,445	1,850,083	1,763,989	1,630,320
After-tax investment cash flow ($)	486,621	246,161	372,531	505,294
After-tax total savings ($)	1,569,054	1,689,023	1,520,249	1,299,716
After-tax discounted net savings ($)	783,817	865,836	767,774	642,846

[a] Refer to Table 4.26 footnote [a].

Table 4.31 A comparison of total costs and savings of four multiple-site rice drying centers after operating for 11 years in Malaysia.

Drying system[a]	IBCF36/5	IBCF24/12	IBCF18/10	IBCF18/20
Breakeven return ($/t)	10.48	15.04	16.01	17.56
Ownership cost (%)	28.7	35.5	41.8	46.5
Before-tax savings ($)	4,074,303	4,074,303	4,074,303	4,074,303
Before-tax expenses ($)	1,700,702	2,333,664	2,362,622	2,495,986
Before-tax net savings ($)	2,373,601	1,740,639	1,711,681	1,578,317
After-tax net savings ($)	1,661,518	1,218,446	1,198,175	1,104,820
After-tax investment cash flow ($)	302,037	536,133	672,094	820,121
After-tax total savings ($)	1,463,901	867,664	758,431	568,229
After-tax discounted net savings ($)	746,714	421,583	352,632	241,477

[a] Refer to Table 4.27 footnote [a].

Table 4.32 After-tax cash flow for operating one 12′x 12′ concurrentflow dryer at a single site in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	128,388	35,186	14,748	107,950
2	135,925	38,705	16,820	114,040
3	143,795	42,575	16,820	118,040
4	151,982	46,833	16,820	121,969
5	160,512	51,516	16,820	125,816
6	169,427	56,668	16,820	129,579
7	178,769	62,334	16,820	133,255
8	188,582	68,568	16,820	136,834
9	198,913	75,425	16,820	140,308
10	209,814	82,967	16,820	143,667
11	221,338	-74,156	2,102	297,596
Total	1,887,445	486,621	168,230	1,569,054

The ownership cost (i.e. the fixed cost of each system) is given as a percentage of the breakeven return. Systems IBCF18/20 and CCF12/1 show high ownership costs of 46.5 and 48.7 %, respectively, because their total investments are high. Conversely, systems with low investment costs, such as the IBCF36/1 and IBCF36/5 systems have low ownership costs of 27.8 and 28.7 %, respectively. Note that the low breakeven return of system CCF12/1 increases the ownership cost while the high breakeven return of the IBCF18/20 decreases the ownership cost.

The before-tax saving ($4,074,303) is the same for all cases since it represents the cost of custom-drying the rice. The savings are achieved by avoiding this payment .

The before-tax expenses include such items as the interest on the loan, the maintenance and repair costs, the fuel costs, the labor costs, the supplies, the housing, the property taxes, and the insurance. The before-tax expenses are lowest for the CCF12/1 and IBCF36/1 at $1,377,303 and $1,431,324, and highest for IBCF18/20 at $2,495,986.

The before-tax net savings data, derived from the savings and expenses, show that more than $2.3 million is earned by each of the single-site systems, and by the IBCF36/5 system. The before-tax savings decrease as systems employ more drying sites, emphasizing the economics of scale.

At the 30 % tax level, all the single-site systems and the IBCF36/5 system generate more than $1.3 million after-tax savings; the other three systems save less than $0.9 million after the eleven years of operation.

The after-tax investment cash flows, and the principal payments less the equipments' salvage costs, follow the same trend as the total costs of investment. The more expensive systems have higher installments.

Subtracting the investment cash flow from the after-tax net savings, results in the after-tax total savings for each system. The ranking of the drying systems in terms of total savings is:

1. IBCF36/1 at savings of $1,689,023
2. CCF12/1 at savings of $1,569,094
3. IBCF24/1 at savings of $1,520,249
4. IBCF36/5 at savings of $1,4463,901
5. IBCF18/1 at savings of $1,299,716
6. IBCF24/12 at savings of $867,664
7. IBCF18/10 at savings of $758,431
8. IBCF18/20 at savings of $568,229.

Discounting the total savings does not change the ranking. It merely accounts for the opportunity cost and risk of the investment, and transforms the total savings to the net present value (Appendix C).

The above analysis has assumed a 30% tax rate. This means that the analysis holds for private ownership of the drying and milling facility. If the facility is public owned, there will be no tax rate. Table 4.33 gives the cash flow

Table 4.33 After-tax cash flow for operating five 36'in-bin counterflow dryers at a single-site government rice mill in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	196,175	17,799	0	178,376
2	204,410	19,579	0	184,831
3	212,960	21,537	0	191,423
4	221,804	23,691	0	198,113
5	230,965	26,060	0	204,905
6	240,466	28,666	0	211,800
7	250,340	31,532	0	218,808
8	260,619	34,686	0	225,933
9	271,339	38,154	0	233,185
10	282,535	41,970	0	240,565
11	294,244	-37,513	0	331,757
Total	2,665,857	246,161	0	2,419,696

Table 4.34 After-tax cash flow for operating the IBCF36/1 drying system at half capacity in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	57,620	17,799	7,474	47,295
2	61,201	19,579	8,507	50,129
3	64,951	21,537	8,507	51,921
4	68,853	23,691	8,507	53,669
5	72,922	26,060	8,507	55,369
6	77,178	28,666	8,507	57,019
7	81,640	31,532	8,507	58,615
8	86,328	34,686	8,507	60,149
9	91,270	38,154	8,507	61,623
10	96,487	41,970	8,507	63,024
11	102,006	-37,513	1,064	140,583
Total	860,456	246,161	85,101	699,396

result for the most favorable case, i.e. IBCF36/1. This table shows that tax savings from equipment depreciation is not applicable to the government drying and milling facility. However, income tax is also not applicable to this facility. Thus, there is a higher total savings of $2,419,696 compared to the $1,689,023 total savings of the privately owned IBCF36/1 facility.

Another assumption made in the analysis is that all the rice produced from the 3,000 ha area is to be dried at the new location(s). If only 50% of the rice is shipped to the new location(s), the economic results will be less favorable. Table 4.34 shows the life-cycle costing analysis for the IBCF36/1 privately owned system receiving rice from only 1,500 ha rather than 3,000 ha. Positive savings are still generated from the first year. The total savings after 11 years of operation is $699,396.

Tables 4.32 to 4.34 and D.1 to D.7 describe the yearly cash savings for each drying system. The total yearly cash savings are obtained from:

$$\text{Total Savings} = \text{Net Savings} + \text{Tax Savings} - \text{Investment cash flow.}$$

For the privately owned drying facilities, serving 3,000 ha of rice field, the IBCF36/1 and the CCF12/1 systems have the highest total savings. System IBCF36/1 uses five in-bin counterflow dryers of 11 m diameter while system CCF12/1 uses one dryer of 3.66 m x 3.66 m cross-section. The IBCF dryers have heights of about 3 m, while the CCF dryer has a height of about 35 m. System IBCF36/1 requires a larger site than system CCF12/1.

When the tubes above the drying bed of the CCF dryer are plugged by dirt and trash, they have to be cleaned out. Rice with high impurities from the Malaysian farmers will necessitate the dryer operators to pre-clean the rice. The in-bin counterflow dryer have a simpler construction and operating mechanism. Reasonable trash content in the rice does not affect its performance. Also, the lower height makes the in-bin counterflow dryer parts more accessible for maintenance.

The simulations of the concurrentflow and the in-bin counterflow dryers show that the latter is approximately 25 % less energy efficient. This is because the concurrentflow dryer is able to use higher, more efficient drying-air temperatures without increasing the grain temperatures above tolerable limits.

Knowledge and experience in the workings of the concurrentflow dryer are essential for the operators; the dryer operates only when full. An operator has to fully understand the dryer so that he/she can estimate when to turn the burners of the various stages on or off. An operator must also be aware of the maximum air temperatures that can be used so that the capability of the dryer may be utilized to the fullest without damaging the rice.

The in-bin counterflow dryer is easier to operate. An operator merely has to set the drying air temperature for each drying pass and maintain the dryer full.

An important advantage of the IBCF dryer is the simple construction of the dryer; it can be manufactured in Malaysia under license. This will reduce the cost, and make the parts readily available locally.

4.4.5 Economic Conclusions

The Malaysian rice industry as a whole is not truly market-oriented but partially politically driven since rice farmers own only 1 to 2 ha of paddy land. Rice sold to the LPN and the private mills have a high impurities content (Loo 1987). Availability of technical personnel in the rice industry is limited due to strong competition from the more profitable manufacturing industries and cash-crop plantations. Therefore, the IBCF36/1 rice-drying system is the preferred choice for the Malaysian conditions.

If a decentralized drying system is required, the IBCF36/5, netting a total savings of $1,463,901, is comparable to the centralized IBCF36/1 system with a total savings of $1,689,023. Further decentralization is possible at a reduced savings. The effect of transportation costs has to be quantified, and considered in comparing the centralized and the decentralized drying systems.

5. CONCLUSIONS

Field experiments with the concurrentflow dryer and the in-bin counterflow dryer were successfully conducted with commercial-sized units.

The simulation of rice drying in Malaysia, using the validated Michigan State University (MSU) multi-stage concurrentflow and in-bin counterflow dryer models, yielded the dryers' capacities and energy efficiencies. Both quantities were employed in the physical design and the economical evaluation of the two drying systems.

In drying rice from 23 % to 13.5 % in three passes (23-19 %, 19-16 %, and 16-13.5 %), under average Malaysian ambient conditions of 29.4°C and 85 % relative humidity, the 3.66 m x 3.66 m three-stage concurrentflow (CCF) dryer and the 5.48 m diameter in-bin counterflow (IBCF) dryer have drying capacities of 1.023 and 0.026 $t/m^2/h$, respectively. Thus, the in-bin counterflow dryer has to have a larger floor area than the concurrentflow dryer in order to match its drying capacity. The maximum inlet air temperatures of the concurrentflow and the in-bin counterflow dryers are 126.7°C and 47.2°C, respectively.

The energy requirement of the three-stage concurrentflow dryer is 3861 kJ/kg water, of the in-bin counterflow dryer

6408 kJ/kg water. Thus, the concurrentflow dryer requires 40 % less fuel to dry the same amount of rice than the in-bin counterflow dryer.

To service a 3,000 ha rice farm in Malaysia which has an average yield of 2.47 t/ha/season while producing two crops per year and harvesting 30 days per season, requires one 3.66 m x 3.66 m three-stage concurrentflow dryer. The number of in-bin counterflow dryers needed to replace the concurrentflow dryer in drying this crop are five, twelve, and twenty if 10.97 m, 7.32 m, and 5.48 m diameter drying bins are employed, respectively.

The estimated total fixed costs of the eight drying systems, listed in ascending order, are: $283,674 for the IBCF36/1 system, $348,064 for the IBCF36/5 system, $429,299 for the IBCF24/1 system, $560,776 for the CCF12/1 system, $582,294 for the IBCF24/1 system, $617,834 for the IBCF24/12 system, $774,514 for the IBCF18/10, and $945,097 for the IBCF18/20 system. (Note: CCF12/1 refers to the 12′x 12′ concurrentflow dryer located at one drying facility while IBCF36/5 refers to five 36′ in-bin counterflow dryers located at five separate drying facilities). Thus, the fixed cost of a drying system increases as the number of dryers and the number of drying centers are increased.

A life-cycle costing analysis of eight privately owned drying systems with the owner in the 30% tax bracket are made. Each drying system handles all the rice from a 3,000 ha rice area with two crops per year. The system's drying cost is compared to the current custom-drying cost in Malaysia of $20.95. The analysis shows positive cash flows every year for each system.

The IBCF36/1 drying system provides the greatest after-tax total savings of $1,689,023; the CCF12/1 drying system follows with a value of $1,569,054. System IBCF18/20, which utilizes a number of the smallest available in-bin counterflow dryers located at the largest number of locations, nets the lowest after-tax savings of $568,229.

The after-tax savings of the centralized drying facilities range from $1,299,716 to $1,689,023. Obviously, they have in general the advantage of the economics of scale compared to the decentralized facilities which generate after-tax savings of $568,229 to $1,463,901. However, by decentralizing the drying facilities at five centers through the IBCF36/5 system, $1,463,901 of after-tax savings is generated compared to custom-drying: this figure falls within the range of the centralized systems' savings.

The concurrentflow dryer, while providing efficient drying in terms of capacity and fuel usage, and utilizing the smallest dryer space, requires high technical expertise on the part of the dryer operator and maintenance crew.

Thus, for technical as well as economical reasons, the in-bin counterflow rice dryer is recommended for rice mills under Malaysian conditions.

6. SUGGESTIONS FOR FUTURE RESEARCH

The only high-capacity continuous-flow dryer type at present employed in Malaysian rice mills is the mixed-flow (LSU) dryer. Field experiments on the mixed-flow dryer, similar to those reported in this study, will yield useful data that can be compared to that of the concurrentflow and the in-bin counterflow dryers.

It has been shown in this study that a validated simulation model of a particular dryer is useful for investigating the performance of the dryer under various ambient and drying conditions. Since the mixed-flow dryer is still the most popular continuous flow rice dryer in the Southeast Asian region, there is a need for an MSU mixed-flow drying simulation model.

Through field experiments and computer simulations of the in-bin counterflow dryer, it is found that this drying system is very suitable for Malaysian physical and economic conditions. Therefore, it is recommended that one in-bin counterflow dryer be field tested in Malaysia.

The main advantage of centralizing the drying facility is the savings due to the economics of scale. This is challenged by the savings in transport costs of the decentralized drying system. There is a need to analyze the actual savings realized by both systems in Malaysia.

APPENDIX A

Table A.1 Experimental drying results of the in-bin counterflow dryer for test T1.

Cycle No.	Cycle Time (h)	Capacity (t/h)	Airflow (cmm/m^2)	Final Moisture Content (% wb)
1	4.42	0.85	12.1	16.9
2	2.37	1.01	12.3	20.0
3	1.93	0.39	11.8	22.6
4	0.63	1.00	11.6	19.4
5	1.70	0.74	11.1	21.4
6	1.15	0.66	11.0	20.6
7	1.75	0.72	11.0	20.3
8	1.78	0.35	11.1	22.4
9	1.38	1.37	11.2	22.6
10	2.20	1.32	11.5	22.0
11	1.67	1.58	11.6	21.4
12	2.30	0.33	12.0	20.0
13	0.27	5.13	12.5	17.8
14	1.72	1.17	12.1	18.4
15	1.00	0.63	12.5	20.6
16	0.63	1.20	12.5	21.4
17	0.45	1.68	12.5	21.0
18	1.53	1.32	12.5	18.4
19	1.10	1.26	12.5	19.3
20	1.47	1.37	13.1	19.4
21	1.38	2.10	13.6	18.8
22	0.82	2.30	13.6	15.4
23	0.57	5.47	14.9	18.2

Table A.2 Experimental drying results of the in-bin counterflow dryer for test T2.

Cycle No.	Cycle Time (h)	Capacity (t/h)	Airflow (cmm/m^2)	Final Moisture Content (% wb)
1	1.68	1.22	12.9	21.4
2	1.08	2.01	13.3	23.3
3	1.02	2.13	13.7	24.9
4	1.47	1.64	13.3	23.0
5	1.50	1.53	12.8	20.6
6	1.50	1.61	13.0	17.8
7	1.50	1.61	12.8	20.4
8	1.47	1.64	13.0	22.6
9	1.22	1.88	13.3	21.8
10	1.07	2.14	13.7	22.0
11	1.22	2.17	14.0	21.6
12	1.45	1.58	13.6	18.6
13	1.17	2.57	13.9	20.2
14	1.18	1.94	13.6	17.4
15	1.37	1.67	13.6	19.4
16	1.27	1.80	13.8	19.2
17	2.12	1.14	13.1	17.2
18	1.07	2.25	13.7	20.0
19	1.28	1.69	13.8	18.4
20	1.30	3.08	14.0	-

Table A.3 Experimental drying results of the in-bin counterflow dryer for test T4.

Cycle No.	Cycle Time (h)	Capacity (t/h)	Airflow (cmm/m^2)	Final Moisture Content (% wb)
1	2.00	1.18	11.9	14.9
2	0.43	5.86	13.1	15.2
3	1.32	1.19	13.2	16.6
4	0.62	3.81	13.3	15.6
5	0.50	1.58	12.3	17.0
6	0.83	3.04	11.9	17.0
7	1.02	4.79	12.1	15.9
8	1.12	0.70	11.9	19.2
9	0.27	2.92	12.0	19.8
10	0.27	5.84	12.0	18.0
11	0.62	1.27	12.1	18.1
12	0.85	2.78	11.6	18.4
13	1.42	1.33	11.9	19.7
14	0.58	0.82	11.9	18.2
15	1.33	3.08	11.9	19.6
16	1.17	2.02	12.8	17.5
17	1.23	3.97	13.3	19.4
18	1.42	4.00	13.8	16.6
19	0.78	1.21	14.2	16.5
20	0.27	6.65	14.45	18.5

APPENDIX B

APPENDIX B

Example of computer output for the in-bin counterflow dryer simulation.

```
COUNTERFLOW? NO=2; YES=1., REFILL=0.
0.                                              0.0000
TIME BETWEEN REFILLS, HOURS:
100.                                          100.0000
BUSHELS PER REFILL:
73.8                                           73.8000
BUSHELS PER CYCLE:
73.8                                           73.8000
COUNTERFLOW GRAIN DRYER SIMULATION
 USING THE WANG-SINGH THINLAYER  EQUATION FOR  RICE
 AND EMC BY ZURITZ/CHEN-CLAYTON

 INPUT CONDITIONS :
     DRYING AIR TEMP, F :
117.                                          117.0000
AMBIENT AIR TEMP, F :
85.                                            85.0000
     AMBIENT REL HUM, DEC :
.85                                             0.8500
    CALCULATED AMBIENT ABS HUM=                 0.0222
    TYPE OF FUEL USED (1=NO.2 FUEL
    2=NAT.GAS; 3=L.P.GAS; 4=BIOMASS):
3.                                              3.0000
    CALCULATED INLET ABS HUM=                   0.0229
    INLET GRAIN TEMP, F:
85.                                            85.0000
    INITIAL MOISTURE, W.B.PERC.:
23.                                            23.0000
TESTWEIGHT LB/BU
49.5                                           49.5000
    FINAL MOISTURE,W.B.PERC.:
19.                                            19.0000
    BED DEPTH,FT:
4.6                                             4.6000
FINES FACTOR; 1-2(1 CLEAN, 2 DIRTY):
1.2                                             1.2000


PRELIMINARY CALCULATED VALUES

AIRFLOW, CFM/SQ FT                39.6529
```

DRY AIRFLOW RATE, LB/HR-FT2 157.8339
INLET MC(DRY BASIS DECIMAL) 0.2987
PLENUM PRESSURE, IN-H2O: 3.8633
SATISFIED WITH DEPTH/PRESSURE COMBINATION? YES=1.; NO=0.
1. 1.0000
MAX.DRYING TIME, HR:
7. 7.0000
OUTPUT INTERVAL,FT:
.5 0.5000
HYBRID DRYING FACTOR,DEC.:
1. 1.0000

CYCLES	1
CYCLE TIME, HRS	0.87
GRAIN DEPTH, FT	4.24
STATIC PRESSURE, IN-H2O	3.66
AIRFLOW, CFM	10090.44
GRAIN DRIED, BUSHELS	73.80
MCWB	18.84
TEMPERATURE, F	114.49
AVERAGE DRYING RATE, BU/HR	84.97
DRYING RATE, THIS CYCLE, BU/HR	84.97

DEPTH	M C	PROD.TEMP	AIR TEMP	AIR U.R.	REL.HUM.
0.54	20.94	110.51	112.63	0.02878	42.10
1.08	22.56	103.60	107.15	0.03541	59.52
1.62	23.93	97.74	98.39	0.04077	100.00
2.16	23.71	94.71	95.70	0.03738	100.00
2.70	23.49	91.41	92.41	0.03357	100.00
3.24	23.30	88.62	89.40	0.03041	100.00
3.78	23.14	86.76	87.24	0.02831	100.00
4.32	23.07	85.76	86.00	0.02717	100.00

STATIC PRESSURE,IN H2O:	3.6563
HORSE POWER,HP/FT2:	0.0465
AVER.AIR TEMP.,F:	96.5395
AVER. PROD. TEMP.,F:	95.2303
AVER. MOISTURE,W.B. PERC.:	23.0392
INLET MOIST. EQUIL.,W.B. PERC.:	7.7724
OUTLET MOIST. EQUIL.,W.B. PERC.:	37.7314
WATER REMOVED,LB/FT2	0.7358
SECO (DRYING ONLY), BTU/LB-H2O:	1504.1211
SECO (WITH FAN), BTU/LB-H2O:	1643.9039
TOTAL DRYING TIME,HR.:	0.8685

IN REFILLED WITH 73.8 BU TO A DEPTH OF 4.6 FT

FTER 0.9 HOURS

CYCLES	2
CYCLE TIME, HRS	0.55
GRAIN DEPTH, FT	4.24
STATIC PRESSURE, IN-H2O	3.66
AIRFLOW, CFM	10090.44
GRAIN DRIED, BUSHELS	147.60
MCWB	18.95
TEMPERATURE, F	114.65
AVERAGE DRYING RATE, BU/HR	104.04
DRYING RATE, THIS CYCLE, BU/HR	134.16

DEPTH	M C	PROD.TEMP	AIR TEMP	AIR U.R.	REL.HUM.
0.54	21.06	110.20	112.76	0.02898	42.10
1.08	22.54	104.20	107.01	0.03564	61.13

1.62	24.04	99.60	99.92	0.04282	99.60
2.16	23.94	98.16	98.66	0.04113	100.00
2.70	23.80	95.97	96.74	0.03865	100.00
3.24	23.59	93.12	94.03	0.03539	100.00
3.78	23.37	90.27	91.11	0.03217	100.00
4.32	23.22	88.01	88.63	0.02965	100.00

STATIC PRESSURE,IN H2O:	3.6563
HORSE POWER,HP/FT2:	0.0465
AVER.AIR TEMP.,F:	99.0308
AVER. PROD. TEMP.,F:	97.8144
AVER. MOISTURE,W.B. PERC.:	23.2195
INLET MOIST. EQUIL.,W.B. PERC.:	7.7655
OUTLET MOIST. EQUIL.,W.B. PERC.:	37.7150
WATER REMOVED,LB/FT2	0.9206
SECO (DRYING ONLY), BTU/LB-H2O:	1963.7822
SECO (WITH FAN), BTU/LB-H2O:	2146.2828
TOTAL DRYING TIME,HR.:	1.4186

IN REFILLED WITH 73.8 BU TO A DEPTH OF 4.6 FT

FTER 1.4 HOURS

CYCLES	3
CYCLE TIME, HRS	0.73
GRAIN DEPTH, FT	4.24
STATIC PRESSURE, IN-H2O	3.66
AIRFLOW, CFM	10090.44
GRAIN DRIED, BUSHELS	221.40
MCWB	18.74
TEMPERATURE, F	115.13
AVERAGE DRYING RATE, BU/HR	102.92
DRYING RATE, THIS CYCLE, BU/HR	100.76

DEPTH	M C	PROD.TEMP	AIR TEMP	AIR U.R.	REL.HUM.
0.54	20.74	111.53	113.58	0.02884	41.30
1.08	22.21	105.66	107.93	0.03526	58.41
1.62	24.03	100.12	100.46	0.04348	82.30
2.16	24.08	99.68	99.80	0.04266	100.00
2.70	24.00	99.17	99.35	0.04205	100.00
3.24	23.93	98.12	98.53	0.04095	100.00
3.78	23.76	96.26	96.91	0.03867	100.00
4.32	23.65	93.79	94.59	0.03605	100.00

STATIC PRESSURE,IN H2O:	3.6563
HORSE POWER,HP/FT2:	0.0465
AVER.AIR TEMP.,F:	101.8389
AVER. PROD. TEMP.,F:	100.8239
AVER. MOISTURE,W.B. PERC.:	23.2917
INLET MOIST. EQUIL.,W.B. PERC.:	7.7426
OUTLET MOIST. EQUIL.,W.B. PERC.:	37.6055
WATER REMOVED,LB/FT2	1.1661
SECO (DRYING ONLY), BTU/LB-H2O:	2350.8347
SECO (WITH FAN), BTU/LB-H2O:	2569.3054
TOTAL DRYING TIME,HR.:	2.1511

IN REFILLED WITH 73.8 BU TO A DEPTH OF 4.6 FT

FTER 2.2 HOURS

CYCLES	4
CYCLE TIME, HRS	0.55
GRAIN DEPTH, FT	4.24

STATIC PRESSURE, IN-H2O	3.66
AIRFLOW, CFM	10090.44
GRAIN DRIED, BUSHELS	295.20
MCWB	18.86
TEMPERATURE, F	115.10
AVERAGE DRYING RATE, BU/HR	109.43
DRYING RATE, THIS CYCLE, BU/HR	135.03

DEPTH	M C	PROD.TEMP	AIR TEMP	AIR U.R.	REL.HUM.
0.54	20.78	111.18	113.48	0.02890	41.41
1.08	22.25	105.57	107.88	0.03528	59.08
1.62	24.14	100.05	100.09	0.04297	83.57
2.16	24.11	100.08	100.14	0.04313	99.38
2.70	24.03	99.77	99.88	0.04278	100.00
3.24	24.02	99.34	99.50	0.04225	100.00
3.78	23.78	98.53	98.84	0.04137	100.00
4.32	23.98	97.06	97.60	0.03974	100.00

STATIC PRESSURE,IN H2O:	3.6563
HORSE POWER,HP/FT2:	0.0465
AVER.AIR TEMP.,F:	102.5267
AVER. PROD. TEMP.,F:	101.6342
AVER. MOISTURE,W.B. PERC.:	23.3458
INLET MOIST. EQUIL.,W.B. PERC.:	7.7442
OUTLET MOIST. EQUIL.,W.B. PERC.:	37.4996
WATER REMOVED,LB/FT2	1.3471
SECO (DRYING ONLY), BTU/LB-H2O:	2551.9718
SECO (WITH FAN), BTU/LB-H2O:	2789.1348
TOTAL DRYING TIME,HR.:	2.6976

IN REFILLED WITH 73.8 BU TO A DEPTH OF 4.6 FT

FTER 2.7 HOURS

CYCLES	5
CYCLE TIME, HRS	0.55
GRAIN DEPTH, FT	4.24
STATIC PRESSURE, IN-H2O	3.66
AIRFLOW, CFM	10090.44
GRAIN DRIED, BUSHELS	369.00
MCWB	18.90
TEMPERATURE, F	115.07
AVERAGE DRYING RATE, BU/HR	113.78
DRYING RATE, THIS CYCLE, BU/HR	135.26

DEPTH	M C	PROD.TEMP	AIR TEMP	AIR U.R.	REL.HUM.
0.54	20.82	110.92	113.41	0.02894	41.51
1.08	22.27	105.45	107.62	0.03533	59.46
1.62	24.05	100.30	100.44	0.04345	86.69
2.16	24.09	100.25	100.32	0.04327	99.50
2.70	24.06	100.06	100.13	0.04298	99.70
3.24	24.06	99.82	99.89	0.04269	99.74
3.78	23.46	99.49	99.61	0.04241	99.79
4.32	24.18	98.83	99.10	0.04172	100.00

STATIC PRESSURE,IN H2O:	3.6563
HORSE POWER,HP/FT2:	0.0465
AVER.AIR TEMP.,F:	102.8174
AVER. PROD. TEMP.,F:	102.0055
AVER. MOISTURE,W.B. PERC.:	23.3562
INLET MOIST. EQUIL.,W.B. PERC.:	7.7460
OUTLET MOIST. EQUIL.,W.B. PERC.:	37.4287

WATER REMOVED,LB/FT2	1.5289
SECO (DRYING ONLY), BTU/LB-H2O:	2703.3061
SECO (WITH FAN), BTU/LB-H2O:	2954.5331
TOTAL DRYING TIME,HR.:	3.2432

IN REFILLED WITH 73.8 BU TO A DEPTH OF 4.6 FT

FTER 3.2 HOURS

CYCLES	6
CYCLE TIME, HRS	0.55
GRAIN DEPTH, FT	4.24
STATIC PRESSURE, IN-H2O	3.66
AIRFLOW, CFM	10090.44
GRAIN DRIED, BUSHELS	442.80
MCWB	18.94
TEMPERATURE, F	115.04
AVERAGE DRYING RATE, BU/HR	116.89
DRYING RATE, THIS CYCLE, BU/HR	135.41

DEPTH	M C	PROD.TEMP	AIR TEMP	AIR U.R.	REL.HUM.
0.54	20.85	110.80	113.36	0.02897	41.58
1.08	22.30	105.23	107.34	0.03534	60.00
1.62	24.13	100.31	100.30	0.04326	85.00
2.16	24.11	100.48	100.53	0.04358	99.33
2.70	24.05	100.28	100.33	0.04328	99.75
3.24	24.08	100.06	100.12	0.04301	99.75
3.78	23.25	99.85	99.91	0.04282	100.00
4.32	24.27	99.52	99.65	0.04246	100.00

STATIC PRESSURE,IN H2O:	3.6563
HORSE POWER,HP/FT2:	0.0465
AVER.AIR TEMP.,F:	102.9474
AVER. PROD. TEMP.,F:	102.1575
AVER. MOISTURE,W.B. PERC.:	23.3455
INLET MOIST. EQUIL.,W.B. PERC.:	7.7476
OUTLET MOIST. EQUIL.,W.B. PERC.:	37.3986
WATER REMOVED,LB/FT2	1.7114
SECO (DRYING ONLY), BTU/LB-H2O:	2820.8047
SECO (WITH FAN), BTU/LB-H2O:	3082.9512
TOTAL DRYING TIME,HR.:	3.7882

IN REFILLED WITH 73.8 BU TO A DEPTH OF 4.6 FT

FTER 3.8 HOURS

CYCLES	7
CYCLE TIME, HRS	0.54
GRAIN DEPTH, FT	4.24
STATIC PRESSURE, IN-H2O	3.66
AIRFLOW, CFM	10090.44
GRAIN DRIED, BUSHELS	516.60
MCWB	18.97
TEMPERATURE, F	115.01
AVERAGE DRYING RATE, BU/HR	119.22
DRYING RATE, THIS CYCLE, BU/HR	135.45

DEPTH	M C	PROD.TEMP	AIR TEMP	AIR U.R.	REL.HUM.
0.54	20.88	110.72	113.32	0.02900	41.65
1.08	22.30	104.98	107.19	0.03536	60.18
1.62	23.98	100.05	99.78	0.04263	88.68
2.16	24.09	100.43	100.38	0.04334	99.32
2.70	23.92	100.39	100.42	0.04337	99.74

3.24	24.20	100.21	100.26	0.04319	99.72
3.78	23.09	100.04	100.09	0.04307	99.94
4.32	24.31	99.86	99.94	0.04286	100.00

STATIC PRESSURE,IN H2O:	3.6563
HORSE POWER,HP/FT2:	0.0465
AVER.AIR TEMP.,F:	102.9236
AVER. PROD. TEMP.,F:	102.1604
AVER. MOISTURE,W.B. PERC.:	23.3239
INLET MOIST. EQUIL.,W.B. PERC.:	7.7489
OUTLET MOIST. EQUIL.,W.B. PERC.:	37.3832
WATER REMOVED,LB/FT2	1.8948
SECO (DRYING ONLY), BTU/LB-H2O:	2914.1472
SECO (WITH FAN), BTU/LB-H2O:	3184.9684
TOTAL DRYING TIME,HR.:	4.3331

IN REFILLED WITH 73.8 BU TO A DEPTH OF 4.6 FT

FTER 4.3 HOURS

CYCLES	8
CYCLE TIME, HRS	0.73
GRAIN DEPTH, FT	4.24
STATIC PRESSURE, IN-H2O	3.66
AIRFLOW, CFM	10090.44
GRAIN DRIED, BUSHELS	590.40
MCWB	18.68
TEMPERATURE, F	115.33
AVERAGE DRYING RATE, BU/HR	116.71
DRYING RATE, THIS CYCLE, BU/HR	101.73

DEPTH	M C	PROD.TEMP	AIR TEMP	AIR U.R.	REL.HUM.
0.54	20.57	112.07	113.88	0.02875	40.95
1.08	22.09	106.11	108.46	0.03508	57.36
1.62	24.36	100.76	101.86	0.04543	79.72
2.16	24.12	100.37	100.40	0.04349	100.00
2.70	23.59	100.41	100.41	0.04335	100.00
3.24	24.26	100.37	100.41	0.04333	99.79
3.78	23.06	100.22	100.27	0.04324	99.64
4.32	24.34	100.15	100.18	0.04318	100.00

STATIC PRESSURE,IN H2O:	3.6563
HORSE POWER,HP/FT2:	0.0465
AVER.AIR TEMP.,F:	103.4079
AVER. PROD. TEMP.,F:	102.6453
AVER. MOISTURE,W.B. PERC.:	23.1992
INLET MOIST. EQUIL.,W.B. PERC.:	7.7329
OUTLET MOIST. EQUIL.,W.B. PERC.:	37.3698
WATER REMOVED,LB/FT2	2.1335
SECO (DRYING ONLY), BTU/LB-H2O:	3021.4381
SECO (WITH FAN), BTU/LB-H2O:	3302.2301
TOTAL DRYING TIME,HR.:	5.0586

IN REFILLED WITH 73.8 BU TO A DEPTH OF 4.6 FT

FTER 5.1 HOURS

CYCLES	9
CYCLE TIME, HRS	0.54
GRAIN DEPTH, FT	4.24
STATIC PRESSURE, IN-H2O	3.66
AIRFLOW, CFM	10090.44
GRAIN DRIED, BUSHELS	664.20

APPENDIX C

APPENDIX C

Explanation of the Capital Investment Program Output

Analysis of the CCF12/1 System

1. The economic savings (discounted dollars) of $783,817 is the after-tax net discounted savings generated by operating the CCF12/1 rice-drying system for 11 years in Malaysia. This value is the total amount of savings made by avoiding the cost of custom-drying, minus the total expenses, interest, payment of principal, and income tax, and then converted to the net present value, taking into account opportunity cost and risk of investment. The positive value indicate that the investment is an economic one.

The annualized breakeven return per unit of $9.96 is the limit in cost of custom-drying, below which the investment in the CCF12/1 system will become uneconomic (i.e. it is cheaper to pay for custom-drying of the rice).

The ownership cost compares the fixed cost per unit (per tonne of rice dried) to breakeven return per unit.

2. The number of units on which the analysis is made is the total rice dried per year i.e. 15,420 tonnes.

3. The depreciation method used must be the one that is allowed by law for the particular type of investment. Tax savings is affected by the method chosen. If desired, the model can choose the best depreciation method. In this analysis, the straight line depreciation is chosen by the user.

4. The number of years after-tax total income is positive is 11 years. Since the CCF12/1 system operates for 11 years in this analysis, savings are realized from year one. Therefore the number of years after-tax total income is negative is 0. In cases where the first few years yield negative after-tax total income ,but positive economic savings over the entire operating period, the potential investor should consider seriously if he/she has the resources to withstand the negative-income years.

5. The before-tax income or cost savings table list the savings made each year by not drying through custom-hire. The amount save is the product of the number of units (tonnes of rice) and the custom-drying cost. The savings increase with time because the custom-drying charges increase yearly.

6. The before-tax cash expenses are made yearly to cover variable costs. The interest payment decreases yearly as the loan balance diminishes. Repairs, fuel and lubrication, and labor increase with time. As the equipment age less insurance is needed.

7. The before-tax net income is the difference between the before-tax savings and the before-tax expenses. Applying the facility owner's 30% income tax level on the before-tax net income yield the after-tax net income.

8. Table 8. tabulates the yearly principal payment of the loan. The loan is fully paid in the tenth year. In the eleventh year, the salvage value of the equipment adds to the savings generated.

9. Tax savings are generated due to the tax exemption on the yearly equipment depreciation. This tax savings is proportional to the facility owner's income tax bracket.

10. After-tax net savings plus the tax savings, and minus the after-tax investment cash flow equals the after-tax total savings. Applying the discount rate to the after-tax net savings to account for opportunity cost and risk (in this case 2% above interest rate or 12%), results in the discounted savings.

CAPITAL INVESTMENT MODEL (Ver AT1) Time: 22:59:55 Date: 06/26/90

**** SUMMARY RESULTS ****

1. Economic savings (discounted dollars) over period of use
   if investment is made = $ 783817
   Annualized breakeven return per unit = $ 9.96
   Ownership cost as a percentage of breakeven return = 48.7

2. Number of units on which analysis was made = 15420

3. Depreciation method used in analysis

4. Number of years after-tax total income is positive = 11
   Maximum annual after-tax total income = $ 297596

   Number of years after-tax Total income is negative = 0
   Minimum annual after-tax total income = $ 0

5. BEFORE TAX INCOME OR COST SAVINGS

Yr.	Primary Income or Cost Reduction	Secondary Income or Cost Reduction	Total
1	323049	0	323049
2	331771	0	331771
3	340729	0	340729
4	349929	0	349929
5	359377	0	359377
6	369080	0	369080
7	379045	0	379045
8	389279	0	389279
9	399790	0	399790
10	410584	0	410584
11	421670	0	421670
Total	4074303	0	4074303

6. BEFORE TAX CASH EXPENSES

Yr.	Int.	Repairs	Fuel & Lub.	Labor	Sup-plies	Housing	Pr Tax & Insur.	Total
1	56078	1374	64196	12390	0	2333	3266	139637
2	52559	1826	65416	13133	0	1941	2717	137592
3	48689	2162	66659	13921	0	1615	2261	135307
4	44431	2474	67925	14757	0	1344	1881	132812
5	39748	2785	69216	15642	0	1118	1565	130074

CAPITAL INVESTMENT MODEL (Ver AT1) Time: 22:59:55 Date: 06/26/90

6	34596	3101	70531	16581	0	930	1302	127041
7	28929	3428	71871	17576	0	774	1083	123661
8	22696	3768	73237	18630	0	644	901	119876
9	15839	4127	74628	19748	0	536	750	115628
10	8297	4503	76046	20933	0	446	624	110849
11	0	4901	77491	22189	0	371	519	105471
Total	351862	34449	777216	185500	0	12052	16869	1377948

7. BEFORE TAX SUMMARY AND AFTER TAX NET INCOME

Yr.	B-T Tot Income	B-T Tot Expenses	B-T Net Income	Net cap Gain or Loss	Tax Rate	A-T Net Income
1	323049	139637	183412	0	30	128388
2	331771	137592	194179	0	30	135925
3	340729	135307	205422	0	30	143795
4	349929	132812	217117	0	30	151982
5	359377	130074	229303	0	30	160512
6	369080	127041	242039	0	30	169427
7	379045	123661	255384	0	30	178769
8	389279	119876	269403	0	30	188582
9	399790	115628	284162	0	30	198913
10	410584	110849	299735	0	30	209814
11	421670	105471	316199	0	30	221338
Total	4074303	1377948	2696355	0		1887445

NOTE: After tax (A-T) net income is equal to before tax (B-T) net income multiplied by (1-(Tax Rate/100)) minus net capital gain or loss multiplied by (Tax Rate/100).

8. CASH FLOWS RESULTING FROM DOWNPAYMENT OR SALVAGE VALUE, PRINCIPAL PAYMENTS, AND INVESTMENT CREDIT RECAP.

Yr.	Dwnpmt or Sal Val	Princ-cipal	Inv Crd Recap	Total
1	0	35186	0	35186
2	0	38705	0	38705
3	0	42575	0	42575
4	0	46833	0	46833
5	0	51516	0	51516
6	0	56668	0	56668
7	0	62334	0	62334
8	0	68568	0	68568
9	0	75425	0	75425
10	0	82967	0	82967
11	74156	0	0	-74156
Total	-74156	560777	0	486621

CAPITAL INVESTMENT MODEL (Ver AT1)   Time: 22:59:55 Date: 06/26/90

9. TAX SAVINGS DUE TO DEPRECIATION AND SECTION 179 DEDUCTION

Yr.	Depreciation	Sec 179 Deduct	Tax Rate	Tax Savings
1	49059	100	30	14748
2	56068	0	30	16820
3	56068	0	30	16820
4	56068	0	30	16820
5	56068	0	30	16820
6	56068	0	30	16820
7	56068	0	30	16820
8	56068	0	30	16820
9	56068	0	30	16820
10	56068	0	30	16820
11	7008	0	30	2102
Total	560679	100		168230

NOTE: Tax savings due to depreciation and Section 179 deduction are calculated by multiplying each one by (Tax Rate/100).

10. DISCOUNTED ANALYSIS OF INVESTMENT

Yr.	A-T Net Income (A)	A-T Inv Cash Flow (B)	Tax Savings (C)	A-T Total (D)	Disc Rate (E)	Discd Values (F)
1	128388	35186	14748	107950	.8929	96384
2	135925	38705	16820	114040	.7972	90912
3	143795	42575	16820	118040	.7118	84019
4	151982	46833	16820	121969	.6355	77514
5	160512	51516	16820	125816	.5674	71391
6	169427	56668	16820	129579	.5066	65649
7	178769	62334	16820	133255	.4523	60278
8	188582	68568	16820	136834	.4039	55265
9	198913	75425	16820	140308	.3606	50596
10	209814	82967	16820	143667	.3220	46257
11	221338	-74156	2102	297596	.2875	85552
TOTAL	1887445	486621	168230	1569054		783817

NOTE: Column (D) is equal to columns (A-B+C),
column (F) is equal to columns (D*E).

APPENDIX D

Table D.1 After-tax cash flow for operating five 36'in-bin counterflow dryers at a single site in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	135,999	17,799	7,474	125,674
2	141,739	19,579	8,507	130,667
3	147,699	21,537	8,507	134,669
4	153,863	23,691	8,507	138,679
5	160,249	26,060	8,507	142,696
6	166,872	28,666	8,507	146,713
7	173,757	31,532	8,507	150,732
8	180,924	34,686	8,507	154,745
9	188,400	38,154	8,507	158,753
10	196,207	41,970	8,507	162,744
11	204,374	-37,513	1,064	242,951
Total	1,850,083	246,161	85,101	1,689,023

Table D.2 After-tax cash flow for operating twelve 24′ in-bin counterflow dryers at a single site in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	123,921	16,937	11,297	108,281
2	130,329	29,630	12,876	113,575
3	137,012	32,593	12,876	117,295
4	143,947	35,853	12,876	120,970
5	151,158	39,438	12,876	124,596
6	158,670	43,382	12,876	128,164
7	166,518	47,720	12,876	131,674
8	174,732	52,492	12,876	135,116
9	183,349	57,741	12,876	138,484
10	192,408	63,515	12,876	141,769
11	201,945	-56,770	1,610	260,325
Total	1,763,989	372,531	128,791	1,520,249

Table D.3 After-tax cash flow for operating twenty 18′ in-bin counterflow dryers at a single site in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	108,322	36,536	15,313	87,099
2	115,251	40,190	17,466	92,527
3	122,514	44,209	17,466	95,771
4	130,071	48,630	17,466	98,907
5	137,948	53,493	17,466	101,921
6	146,184	58,842	17,466	104,808
7	154,820	64,726	17,466	107,560
8	163,897	71,199	17,466	110,164
9	173,466	78,319	17,466	112,613
10	183,574	86,151	17,466	114,889
11	194,273	-77,001	2,183	273,457
Total	1,630,320	505,294	174,690	1,299,716

Table D.4 After-tax cash flow for operating five 36′ in-bin counterflow dryers at five separate sites in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	120,845	21,839	9,164	108,170
2	126,240	24,023	10,439	112,656
3	131,841	26,426	10,439	115,854
4	137,625	29,068	10,439	118,996
5	143,611	31,975	10,439	122,075
6	149,815	35,173	10,439	125,081
7	156,262	38,690	10,439	128,011
8	162,977	42,559	10,439	130,857
9	169,987	46,815	10,439	133,611
10	177,317	51,496	10,439	136,260
11	184,998	-46,027	1,305	232,330
Total	1,661,518	302,037	104,420	1,463,901

Table D.5 After-tax cash flow for operating twelve 24′ in-bin counterflow dryers at twelve separate sites in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	79,490	38,766	16,246	56,970
2	84,988	42,643	18,532	60,877
3	90,732	46,907	18,532	62,357
4	96,676	51,598	18,532	63,610
5	102,843	56,758	18,532	64,617
6	109,268	62,433	18,532	65,367
7	115,987	68,677	18,532	65,842
8	123,043	75,544	18,532	66,031
9	130,471	83,099	18,532	65,904
10	138,317	91,409	18,532	65,440
11	146,631	-81,701	2,317	230,649
Total	1,218,446	536,133	185,351	867,664

Table D.6 After-tax cash flow for operating twenty 18′ in-bin counterflow dryers at ten separate sites in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	71,313	48,597	20,358	43,074
2	77,815	53,457	23,232	47,590
3	84,645	58,803	23,232	49,074
4	91,746	64,683	23,232	50,295
5	99,154	71,151	23,232	51,235
6	106,907	78,266	23,232	51,873
7	115,056	86,093	23,232	52,195
8	123,655	94,702	23,232	52,185
9	132,756	104,172	23,232	51,816
10	142,419	114,590	23,232	51,061
11	152,709	-102,420	2,904	258,033
Total	1,198,175	672,094	232,350	758,431

Table D.7 After-tax cash flow for operating twenty 18′ in-bin counterflow dryers at twenty separate sites in Malaysia.

Year	Net Savings ($)	Investment Cash Flow ($)	Tax Savings ($)	Total Savings ($)
1	57,606	59,301	24,836	23,141
2	64,931	65,231	28,350	28,050
3	72,650	71,754	28,350	29,246
4	80,701	78,929	28,350	30,122
5	89,122	86,822	28,350	30,650
6	97,966	95,504	28,350	30,812
7	107,296	105,054	28,350	30,592
8	117,176	115,560	28,350	29,966
9	127,675	127,116	28,350	28,909
10	138,867	139,828	28,350	27,389
11	150,830	-124,978	3,544	279,352
Total	1,104,820	820,121	283,530	568,229

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