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the agronomy of rice plants, especially the genetics, breeding, cultivation, diseases, and insects that attack both the rice plant and the stored grain, will find this edition helpful in their search for new knowledge.

A new chapter on weed management, written by Dr. Davis E. Bayer, presents useful information in dealing with the weed problem in rice production.

Harvesting, drying, and milling of rough rice are important procedures for successful handling of rice grains. Methods related to these procedures are presented in Chapter 9 of Volume I. Dr. James I. Wadsworth of the Southern Regional Research Center, USDA-ARS, has contributed an excellent Chapter 10 on rice milling. The physical and chemical properties of rice caryopsis are presented in Chapter 11 of Volume I. The utilization aspects of the rice cereals are presented in Volume II.

I acknowledge the excellent cooperation of the contributors to this edition, who have generously provided their knowledge, experience, and time to the readers. Many friends have provided information and offered assistance in preparing and editing the contents. I wish to thank them all for their kindness and assistance. The California Rice Growers Association of Sacramento, California, and colleagues in the University of California—Davis Departments of Food Science and Technology and of Agronomy and Range Science helped greatly in completing the editing of this edition. I appreciate the assistance of Geyun Tang, Dr. Mei C. Huang, Dr. Ginguo Hu, Dr. Pran N. Vohra, Professor Wu Wang, Patricia J. Bailey, Mary Miranda, Diane King, Susan Torguson, Karen Jo Hunter, Carol Cooper, Clara Robison, and Arlene Hamamoto who have worked tirelessly in editing, proofreading, and preparing the manuscripts.

The encouragment and advice of Dr. R. L. Merson and Dr. Duane S. Mikkelsen in revising *Rice* are greatly appreciated.

Davis, California

B. S. Luh

CONTENTS

1

Overview and Prospects of Rice Production

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The first chapter in the 1980 edition of this book, entitled "Rice in its temporal and spatial perspectives" (Lu and Chang 1980) has provided considerable detail on crop history, world production, and supply and demand up to 1978. Subsequent years saw a continuing trend in the spread of the high-yielding varieties (HYVs), rise in grain yield, increase in world production, and expansion in consumption and international trade. This chapter highlights such changes during the past decade. Rice statistics were based mainly on the Food and Agriculture Organization's *World Crop and Livestock Statistics* (FAO 1987), *Quarterly Bulletins of Statistics* (FAO 1988 and 1989), and the *World Rice Statistics 1987* of the International Rice Research Institute (IRRI 1988).

RICE PRODUCTION

World Production

Global rice production hovered between a high of 484.9 million tons of rough rice in 1988 and 377.3 million tons in 1979. The production trend from 1979 to 1988 was marked by three distinct periods: a relatively steady climb from 1979 through 1986, a marked decline in 1987, and a marked

9

Harvest, Drying, and Storage of Rough Rice

C. Y. Wang
Nabisco Brands, Inc.

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The importance of postharvest management of food grains is underscored by the fact that large food losses occur in the world due to poor grain-handling techniques. Therefore, the harvesting, drying, and storage of rice should receive serious attention. This chapter provides some guidelines for achieving this goal.

The harvesting of rice is carried out by manual labor in most rice-growing countries. On the other hand, combines are used to harvest and thresh rice in developed countries with mechanized agriculture. The section on harvesting in this chapter addresses the mechanized rice harvesting conditions prevalent in California. Pillaiyar (1988) has discussed postharvest operations in underdeveloped countries.

Rice processing consists of several unit operations such as drying, husking, milling, and polishing. During these operations, various parts of the kernel are removed. Over the years, a terminology has developed to describe the grain at different stages in the process. The grain, after it comes from the field, is called rough rice or paddy. Amounts of rough rice may be expressed as bags (100 lb), bushels (45 lb), or barrels (162 lb). After the hull or husk is removed, the product is called brown rice. Milled or white rice is what remains after the bran and part of the germ have been removed during milling. White rice is composed of whole and broken kernels. Whole kernels are referred to as head rice, and head yield is the

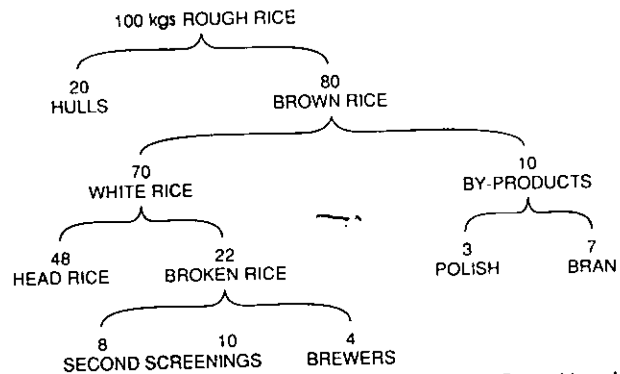

Figure 9-1. Product fractions from standard milling of rice. From Henderson (197

quantity of unbroken kernels milled from a specified amount of rough rice. The various parts of rice during processing are shown in Fig. 9-1.

An important quantitative factor in drying rice is moisture content. The measure of moisture content can be expressed as a wet-basis or a dry-basis number. The wet-basis measure specifies the quantity of water in a solid as a percentage of the total wet weight. Thus, the percentage of wet-basis moisture content (%MCwb) is

$$\%MCwb = \frac{\text{total wet weight—dry weight}}{\text{total wet weight}} \times 100 \quad (1)$$

and the percentage of dry-basis moisture content (%MCdb) is

$$\%MCdb = \frac{\text{total wet weight—dry weight}}{\text{dry weight}} \times 100 \quad (2)$$

The relationship between wet- and dry-basis moisture content is shown in Fig. 9-2. Moisture content expressed on a wet basis has traditionally been used by rice growers, drier operators, and processors. Dry-basis moisture content is generally used in research on drying rice because the denominator in the working equation is independent of the quantity of water in the grain.

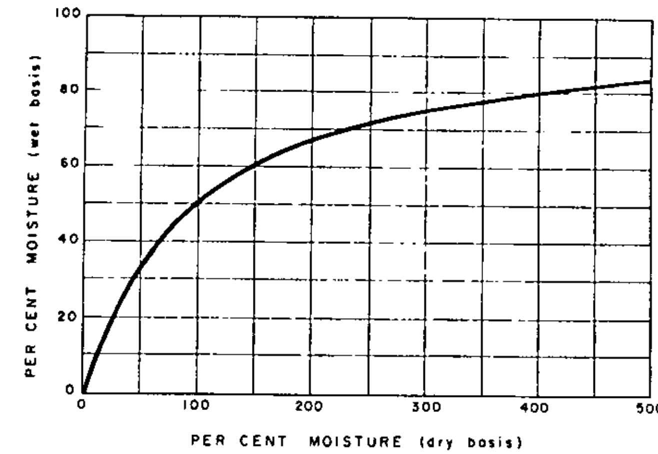

Figure 9-2. Relationship between wet- and dry-basis moisture contents.

RICE HARVESTING

Many factors must be considered to obtain an optimum rice harvest. The grain must be mature, high in quality, and have the proper moisture content. The soil should also be sufficiently dry to support the harvesting and field transport equipment. Careful planning can help to insure that these conditions prevail simultaneously. However, in spite of all precautions and the best planning, unusual or unexpected weather conditions may upset good harvesting.

The cultivation of early maturing rice varieties may be desirable because they help to extend harvest periods and allow grain to be gathered under favorable weather and field conditions. In California, the rice head yields of early-maturing varieties may be reduced by high daytime temperatures and dry north winds that can dry the rice field rapidly and make it difficult to harvest the crop at an optimum moisture content. Late-maturing varieties are not exposed to the extreme variations in the day–night temperatures and humidities that cause rapid field drying.

Preharvest Quality

The preharvest quality of paddy rice helps its postharvest quality, which in turn determines the income rice growers receive in the United States. Maximum head yields are next to crop yields in economic importance. The physical quality of rough rice is dependent on variety, stage of maturity at harvest, moisture content, and physical damages (impact, abrasion, and stress) caused during the harvest, handling, transport, processing, and storage of the grain. All varieties of rice tested in California reach a maximum head rice yield at a moisture content slightly higher than when maximum crop yield occurs. Variety, day and night grain temperatures during the maturing period, planting rates, germination rates, water management, plant population, and weed competition all affect the uniformity of maturation and consequent grain quality.

Rice is harvested at 20 to 27% MCwb in most countries. Rice does not mature simultaneously in an entire field, an individual plant, or even on individual panicles. Chau and Kunze (1982) measured the moisture contents of grains from a rice plot during a harvesting period. They found that differences of 15 to 20% MCwb existed between panicles in the same plot. If the harvest were delayed until all kernels were mature, the early-maturing kernels would become overripe and the overall quality would decrease. Overripe kernels, generally identified by moisture contents below 22% MCwb for early-maturing varieties in California, are subject to field cracking if not harvested promptly when they are mature. Most early-maturing rice grown in California should be harvested at an average moisture content of 24 to 26% MCwb when the highest daytime temperatures are over 23.9°C (75°F). Later in the season (after October 10 in California), when maximum daily air temperature drops below 23.9°C (75°F), the late-maturing rice varieties can be harvested at low cylinder speed (609.6 m/min) even when the grain moisture content is as low as 13 to 14% MCwb and still maintain high head rice yields.

Research on rice grown in the southern United States, India, Surinam, and the Philippines shows that most varieties have reduced head yields after reaching a certain maturity. Kunze (1979) demonstrated that the exposure to varying temperatures and humidities results in lower head yield as lower moisture contents are reached. It appears that harvesting procedures should be determined for each variety grown in each climatic region. Appropriate harvest timing, harvester cylinder speed, and clearance adjustments should be prescribed to minimize impact damage in the harvester at various stages of maturity.

Harvest Preparation

Various harvest-related factors such as variety, planting time, local weather patterns, soil type, field water temperature and management, and date of heading affect maturity. After the planting date is fixed, the next critical observation regarding harvest is the date of the "first heading" when approximately 10% of rice heads have emerged. In California, crops of average yield should be ready for harvest 45 to 55 days after the first heading. Tropical rice is usually harvested 30 days after flowering (50% flowering is considered as the first day), but in cooler climates maximum head yield is attainable by harvesting up to 60 days after flowering (Juliano 1972).

After the date of maturity is estimated, field draining is given primary consideration. This draining must be related to the maturation characteristics of the variety, the expected weather, the soil type, the field characteristics for draining surface water, and the effects of plant evapotranspiration on drying the soil surface. The proper selection of a draining date is important because the soil must be sufficiently dry to support the harvesting and transport machinery when the grain is ready to be harvested. The final decision for draining is made with the knowledge and experience of individual growers and farm advisors. If the field is drained too early, the rice plants will run short of moisture before maturing.

After the field has been drained, the moisture content of rice is monitored as it reaches maturity. When draining, the moisture content may be 30 to 50% wb. The grain moisture content will drop approximately 1% wb/day when the grain has a high moisture content and the weather is hot and dry. When the weather is cool and overcast or the rice moisture content is 20 to 25% wb, the moisture loss may be as low as 0.5% wb/day. Rain or dew may cause an increase in grain moisture content.

Harvesting should commence at 24 to 26% MCwb, particularly with early-maturing varieties harvested during hot dry periods in California. Minimum cylinder speed should be used except in an emergency, especially when moisture contents drop below 22% wb and daytime temperatures exceed 23.9°C (75°F). This precaution is not so important when the moisture content is 24 to 26% wb. Research carried out at the International Rice Research Institute (IRRI) on cylinder types and speeds indicates that about 25% of the kernels will be ruptured if the rice is at 22% MCwb and the cylinder speed is 1280.2 m/min, compared to 5% at 609.6 m/min. Related work being conducted at the Agricultural Engineering Department at the University of California, Davis, indicates similar trends. A relationship appears to exist between the rate of drying resulting in internal kernel stresses and the potential for damage from impact in the cylinder of the rice harvester.

Harvesting begins each day when the dew is off the plants. In California, this is usually at about 10 to 11 A.M. Pacific Standard Time (PST). Harvesting is usually stopped when dew begins to form at 8 to 9 P.M. If the sky is overcast or a dry north wind has been blowing all night, these schedules may change. Operators will adjust the height of cut, forward speed, and reel speed to reflect changes in the height of the plants. Other factors affecting the harvesting operation include stem thickness, lodging, yield, and rice variety.

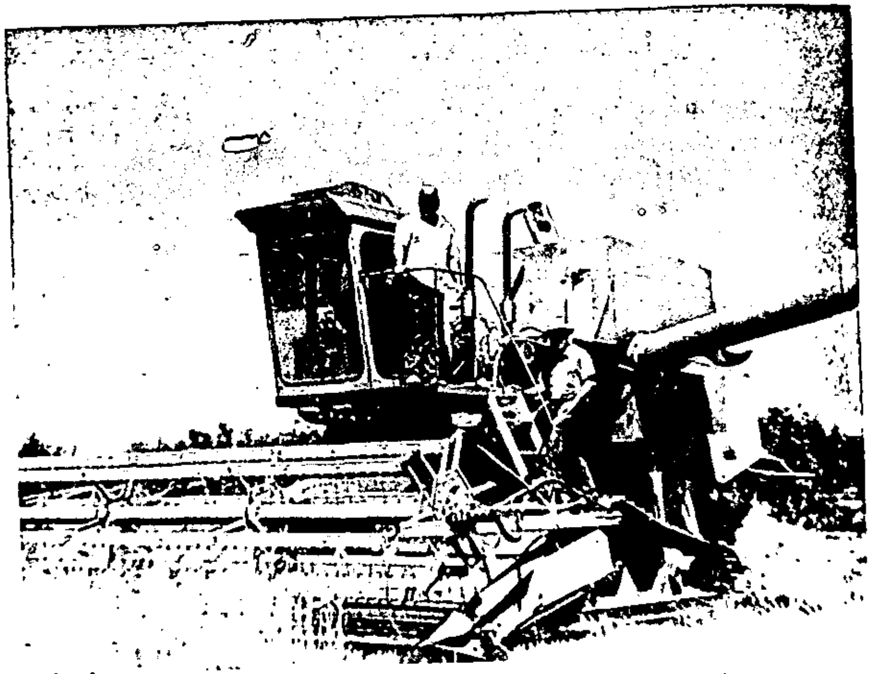

Figure 9-3. Combine in grain field with 4.87-m header.

Rice Harvesters

Rice harvesters have been developed over the years from the binders and stationary-type threshers used in the early days of grain threshing to self-propelled combines that directly cut and thresh rice. Most of the major farm machinery manufacturers make grain harvesters for small-grain harvesting. With certain modifications and special traction units, headers, conveyors, straw walkers, and shoe design, these machines are used for rice harvesting. In use in California are combines designed and built specifically for harvesting rice. They are large, high-capacity, self-propelled combines with full track support that can generally operate under wet field conditions (Figs. 9-3 and 9-4).

Two types of cylinders are available for rice harvesting in the United States. These are the rasp bar and the spike-toothed cylinder. Practically all rice in California is harvested with spike-toothed cylinders. This is partially due to the large volumes of straw produced in the high-yielding California rice fields and the easier cleaning a spike-toothed cylinder allows. In addition, the harvesting process may be a little more efficient with the spike-toothed cylinder in removing the grain from the straw.

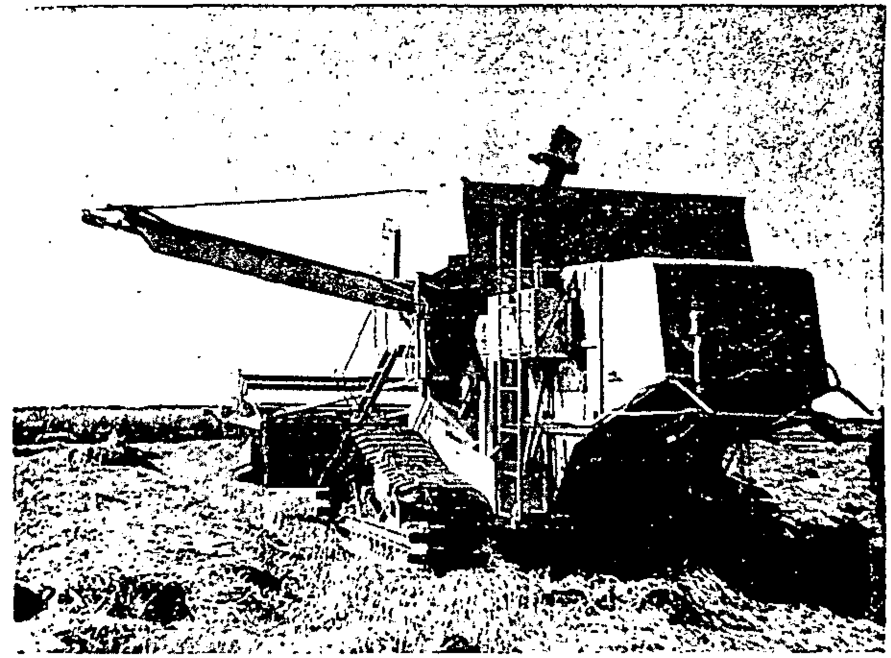

Figure 9-4. Rice combine with 5.48-m header.

Small Japanese harvesters often have wire loop cylinders which, for slow-speed cylinder operation with hold-on systems (the straw does not pass through the cylinder), result in an efficient harvest with a high-quality product.

IRRI has been conducting research on axial-flow-type harvesters and stripper harvesters for a number of years. Axial-flow harvesters feed the grain and straw through inclined cylinder(s) mounted longitudinally in the harvester as compared to conventional cylinders that are mounted crosswise to the movement of the harvester. This method eliminates the conventional straw walker.

Research on stripper harvesters, conducted at the University of California, Davis, indicates that they have the advantage of removing the grain from the plant without cutting the stem. This allows the grain to be removed at lower cylinder speeds with less grain damage. The total machinery and overall weight are considerably less than the conventional harvesters. These harvesters appear to operate well but have problems with lifting lodged rice and feeding it into the stripper cylinder. New short-statured varieties that have more standing rice at harvest may improve the prospects for this type of machine, although the shorter stem may create feeding problems.

For the present, it appears that the conventional spike-toothed cylinder harvester, with suitable modifications made by manufacturers and growers, will be used for harvesting most of the rice in the highly mechanized agricultural areas of the world. Manual methods and small hand-feed machine harvesters continue to be best suited for areas where rice is grown on small individual plots of ground and where labor is available. For more information on rice harvesting methods in developing countries, the reader may refer to Araullo et al. (1976) and Pillaiyar (1988).

Postharvest Management

When widely varying maturity occurs in a rice field at harvest, the harvested grain should be quickly transported to the drier and given priority in the drying schedule. The importance of this has been demonstrated by Kunze and Parsad (1976). In their tests, grain ruptured in storage when high moisture kernels were stored in contact with low moisture kernels. The high humidity produced in the vicinity of the high moisture grain was sufficient to rupture low moisture kernels. This may occur within a few hours, depending on the moisture differentials.

Field transport equipment has been developed for the bulk handling of rice. These units allow high-speed transport from the harvester to waiting trucks while keeping the harvester in continuous operation. Road transport trucks move the crop to the driers, since the rice moisture must be reduced from approximately 24 to 26% MCwb down to 13 to 14% MCwb for safe storage. The risk of heat damage (i.e., discoloration of milled rice grains, altered texture, rapid growth of microorganisms, and low milling yield) is always present in high-moisture rice and early transport to the drying facility is therefore important.

RICE DRYING

Equilibrium Moisture Content

The equilibrium moisture content of rice, commonly abbreviated as EMC, refers to the quantity of moisture in the product when it is at equilibrium with the surrounding air. The EMC of rice will depend on the air temperature and humidity, grain variety, maturity, and previous history. In addition, EMC will depend on whether or not the rice had to adsorb or desorb moisture to achieve equilibrium. The EMC achieved by desorption will be higher than that achieved by adsorption. This phenomenon is referred to as a hysteresis effect.

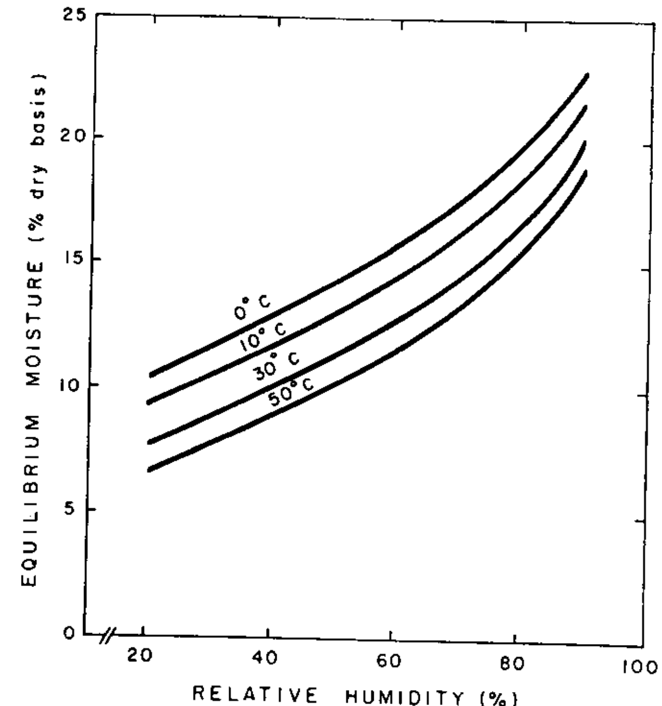

Figure 9-5. Equilibrium moisture content of rough rice. From Pfost et al. (1976).

Zuritz and Singh (1978) reviewed various methods described in the literature for evaluating EMC. They experimentally determined constants in the following EMC equation for medium grain rough rice. Figure 9-5 shows EMC curves generated by Pfost et al. (1976).

$$1 - RH = \exp\left[- \left(1 - \frac{T_A}{T_c}\right)^f \frac{g}{T_c} M_{cp}^{kT_A^m} \right] \quad (3)$$

where

RH	relative humidity, decimal
T_A	temperature (K)
T_c	= 647.1K, critical temperature of water
f	= −26.1911
g	= 4.49488×10^{-8}
k	= 2.2244×10^{6}

m = −2.4160
M_{ep} equilibrium moisture dry basis (percent)

Rough rice consists of an outer husk layer made of SiO_2, a middle layer of fibrous bran, and an inner core of white rice (mostly starch and some protein). The EMC of rice obtained in laboratory is an overall average moisture content of these three different materials and is called the static EMC. During multipass drying operations, only the husks on the surface are at equilibrium with the local air temperature and relative humidity. To account for the differences, Wang (1978) used a dynamic EMC in the simulation of a thin-layer rice-drying process.

Rice-Drying Methods

In this section different types of rice driers are discussed, and some recommendations for operating them are presented. Note that no single set of operating instructions applies to any particular type of drier. Establishing a drying procedure is a situational proposition; many factors such as ambient air conditions, the quantity of grain which has to be dried, and the expected use of the grain must all be considered. Drier operating methods established for a certain location, rice variety, and time of year may be inappropriate for another situation. Two types of mechanical driers are in use in various parts of the world: fixed-bed driers and continuous-flow driers.

Fixed-bed driers

Fixed-bed driers are used for complete on-farm drying, or for finish drying after the major step of moisture removal has been completed in a continuous-flow drier. After drying, these driers may also be used for grain storage. Two common types of fixed-bed driers used in California, having either circular or rectangular bins, are shown in Figs. 9-6 and 9-7. The depth of grain in fixed-bed driers may vary, but 4.3 to 6 m is the maximum practical depth (Henderson and Parsons 1974). Grain in a fixed-bed system is dried with forced air, which may or may not be heated. Grain quality and drying time are affected by the temperature and relative humidity of the drying air. Figure 9-8 indicates that the number of whole kernels in milled rice increases with the humidity of the drying air and decreases with the drying air temperature. Figure 9-9 shows the effect of air temperature and humidity on drying time.

Circular bins (Fig. 9-6) are constructed with perforated floors, and a high-pressure area is created under the grain by a fan attached to the structure. Stirring devices may be added to the bin to aid drying by grain mixing. Drying air is pulled in from outside and forced up through the rice;

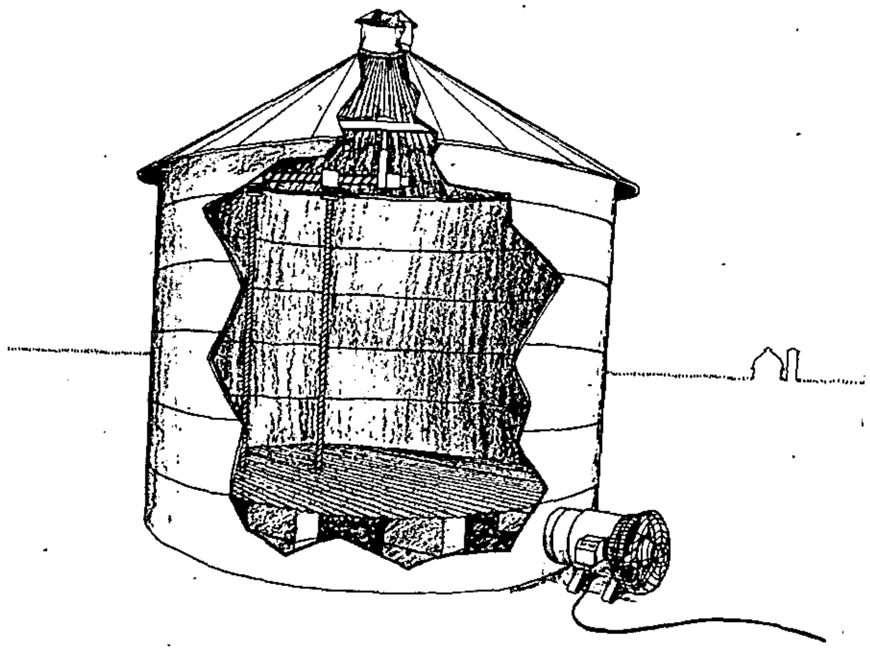

Figure 9-6. Circular bin with stirring device.

the moistened air exits through the top of the bin. Supplemental heaters are usually added to systems of the type shown in Fig. 9-6. These heaters are used when the relative humidity of ambient air is too high to make it suitable for drying. When high-moisture air is used in a fixed-bed drier, it can rewet the rice and cause serious quality deterioration.

Large rectangular bins (sometimes called flats) of the type shown in Fig. 9-7 are usually not designed with supplemental heating equipment. These systems are used for finish drying (removal of moisture after column drying) and storage of rice. The walls and floor of these structures are normally made of concrete. Large fans are located outside the bin and air distribution tunnels are placed from wall to wall on the floor of the bin.

Maintaining the proper air flow when drying rice is vital. If the air flow is insufficient, the rice may spoil before the storage moisture content is reached. Rice provides a resistance to air flow that must be overcome by applying positive pressure at the air inlet to the grain or negative pressure at the air outlet. Resistance to air flow is evidenced as a drop in pressure as the air travels through the bed.

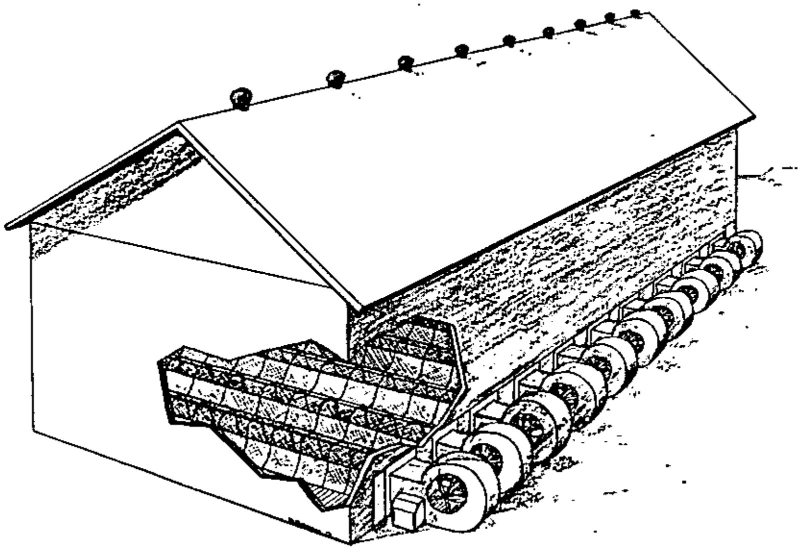

Figure 9-7. Rectangular bin for drying rice.

Continuous-flow driers

Most of the rice produced in the United States is dried commercially in continuous-flow driers. These driers use forced heated air as drying medium. Two common continuous-flow driers are the mixing and nonmixing types. A nonmixing columnar-type drier is shown in Fig. 9-10. The rice flows by gravity in a straight path between two screens. The grain flow rate is controlled by a variable-speed discharge roll. The grain is taken away from the drier with a screw conveyor. This drier is sometimes called a "cross-flow" drier because air is forced to flow across a moving bed of rice. The screens are generally 15.2 to 22.9 cm apart, and the drier may be 12.2 m high and 3 to 3.7 m wide. The nonmixing column-type drier is probably the most common commercial rice drier in use today.

A mixing-type columnar drier that uses baffles is presented in Fig. 9-11. Another mixing-type drier designed at Louisiana State University is shown in Fig. 9-12. In this drier, rice flows downward over inverted V-shaped air channels. Air flows in and out alternate rows of channels, and

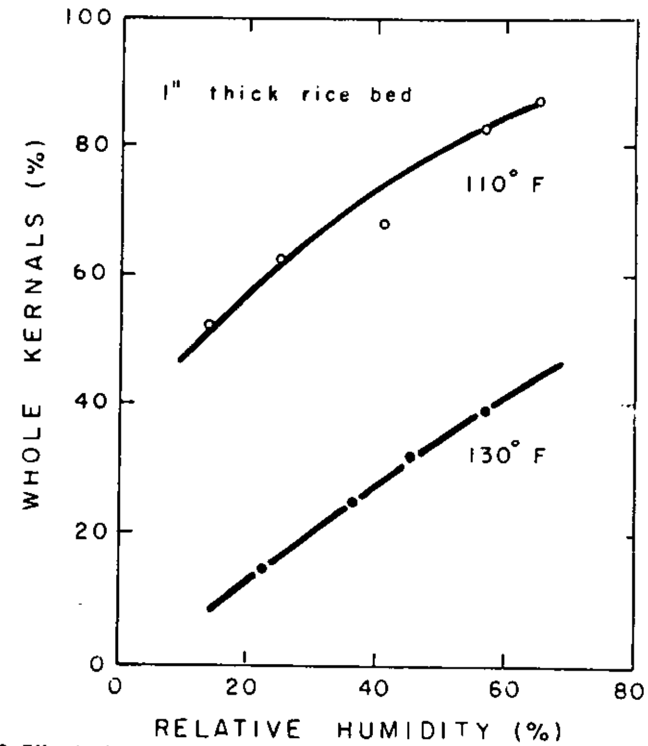

Figure 9-8. Effect of drying-air temperature and relative humidity on percentage of whole kernels in milled rice. From Henderson (1957).

mixing is accomplished because the inlet and outlet air ducts are offset from one another.

In terms of grain quality the mixing-type driers have an advantage over the nonmixing type. In the nonmixing columnar drier (Fig. 9-10) the grain flows straight downward, continuously exposing the grain on the air inlet side of the screen to the hottest air. Thus, the grain on the air exit side of the drier will be cooler and wetter than the grain on the air inlet side. This may result in some of the rice being overdried while the remaining portion would be underdried. The mixing-type driers do not have this limitation. In the baffle-type drier (Fig. 9-11) rice takes a zig-zag path downward. With this type of movement, individual kernels are not continuously exposed to the hottest drying air. The same effect occurs in the Louisiana State University drier (Fig. 9-12) because the air channels divert the path of any particular kernel. Grain mixing promotes more uniform drying of rice.

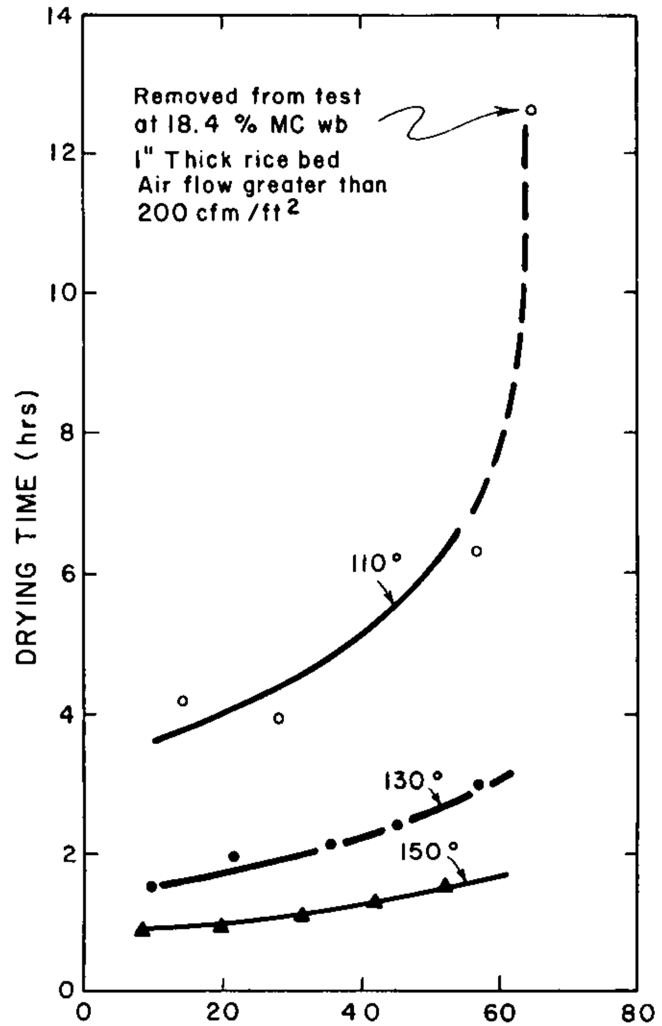

Figure 9-9. Time required to dry rough rice from 24% to approximately 13.5% moisture content at air temperature and relative humidity noted. From Henderson (1957).

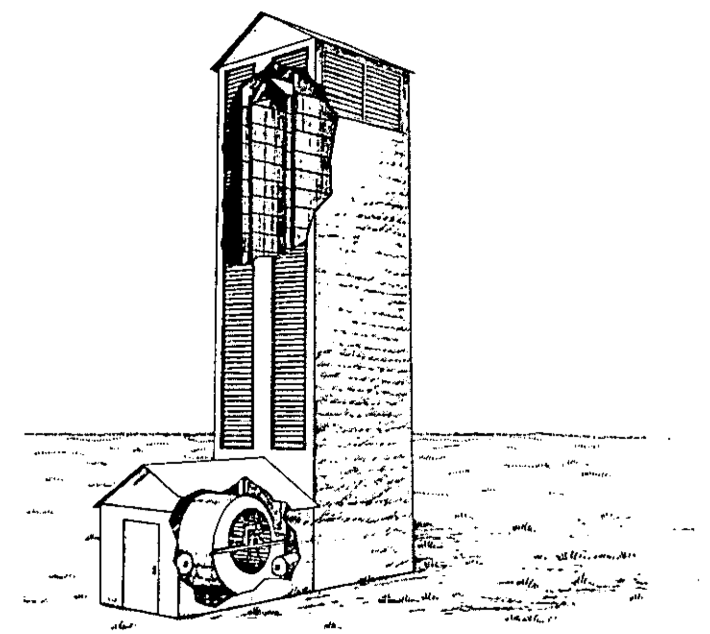

Figure 9-10. Nonmixing-type rice drier.

No single set of operating instructions can be formulated for controlling a continuous-flow drier. Optimum conditions must be determined at each site by test drying the particular variety of rice being processed. The procedure basically involves determining the head yield obtained when rice is dried under various drier conditions.

Continuous-flow rice driers are usually operated on a multipass basis. The moisture content of rice may be reduced 2 to 4% (dry basis) each time it passes through the drier. Between passes, rice is held for a short period to allow the kernel moisture gradients developed during drying time to be reduced. This holding period, which may be as long as 24 h, is referred to as tempering. To increase drier output, it may be desirable to temper the rice for as short a period as possible. Figure 9-13 shows the effect of time and temperature on the head yield of short grain rice. The data indicate that 4-h tempering periods may be adequate if the rice is tempered at 40.6°C (105°F). Steffe et al. (1979) determined that a tempering time of less than 3 h was adequate in multipass drying of medium-grain rough rice.

Fast drying induces rice checking which ultimately reduces head yield.

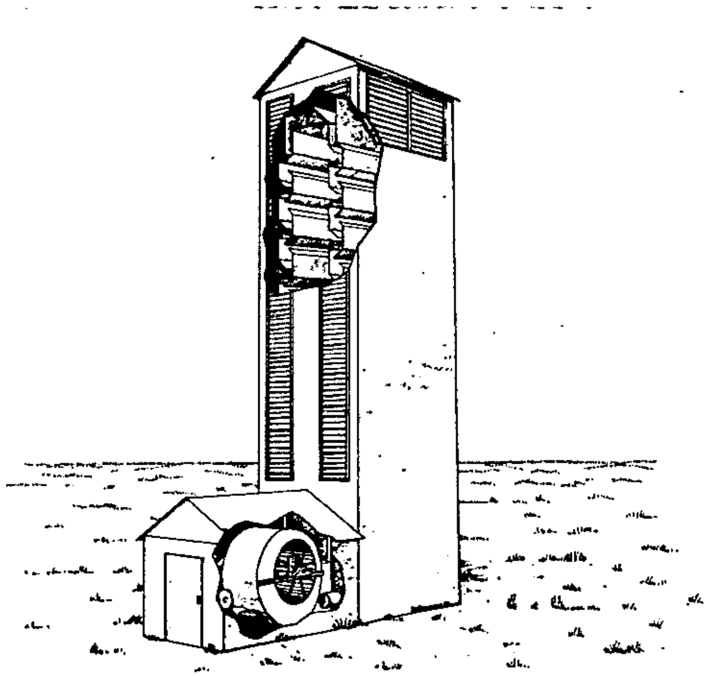

Figure 9-11. Mixing-type (baffle) rice drier.

In multipass drying, the number of drier passes and the quantity of moisture to be removed during each pass is usually determined by the individual drier operator. Many factors, such as drier capacity, quantity of rice to be dried, and moisture to be removed, should be considered in making this decision. When deep-bed driers are used for finish drying, only one pass may be necessary. According to Kunze and Calderwood (1985), typical air flow rates are 187×10^{-5} to 416×10^{-5} $m^3/s \cdot kg$ in nonmixing driers and 73×10^{-5} to 161×10^{-5} $m^3/s \cdot kg$ in the mixing type; air inlet temperatures up to 65.6°C (150°F) in mixing driers and 54.4°C (130°F) in nonmixing driers are common.

Drier configurations other than cross-flow, such as concurrent-flow and counterflow, have been investigated for drying corn. Thompson et al. (1969) made a comparison of cross-flow, concurrent-flow, and counterflow grain driers. Counterflow and concurrent-flow driers are shown in Fig. 9-14. In a counterflow drier, the grain and the air flow are in opposite directions; in a concurrent flow drier the grain and the air flow are in the same direction. The concurrent flow drier has the advantage of causing

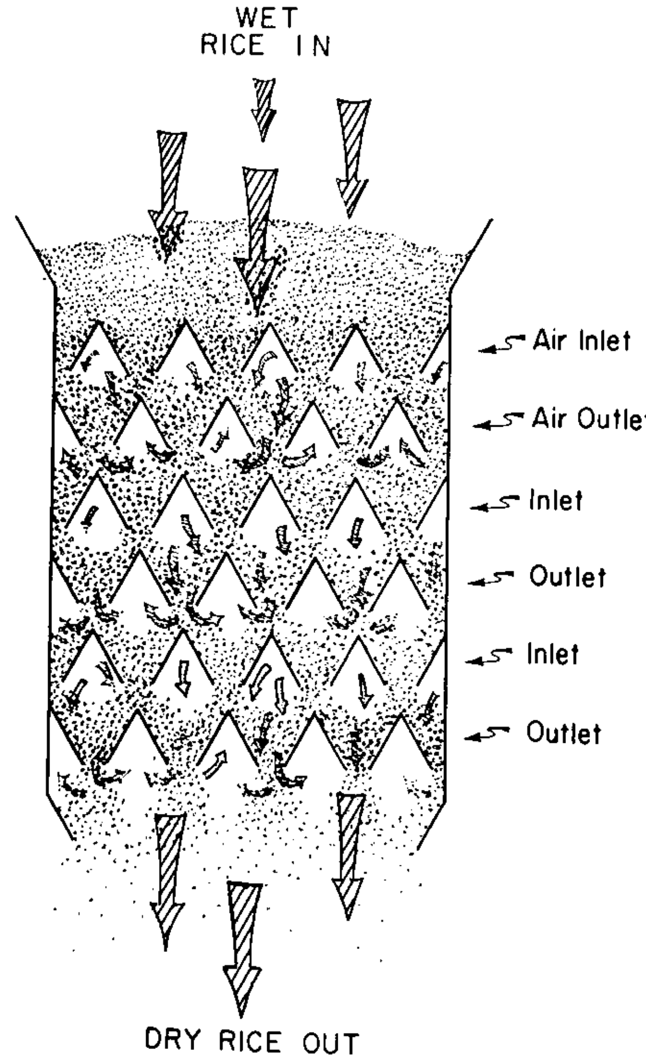

Figure 9-12. Mixing-type drier designed at Lousiana State University.

the hottest air to come in contact with the wettest grain. Bakker-Arkema et al. (1982) described a commercial-sized concurrent-flow rice drier consisting of three heat-then-tempering stages with the final tempering being replaced by a counterflow cooling. The counterflow drier appears to have the potential for removing more moisture per meter of drying bed than concurrent-flow or cross-flow driers.

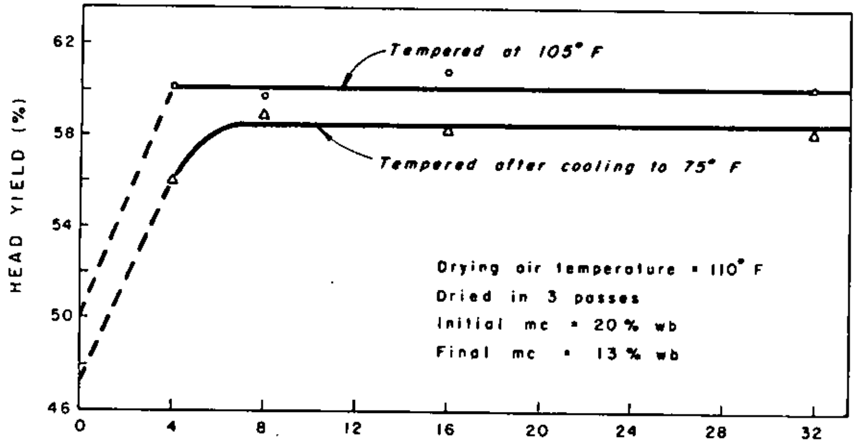

Figure 9-13. Head yield when tempering short-grain rice at various times and temperatures. From Wasserman et al. (1964).

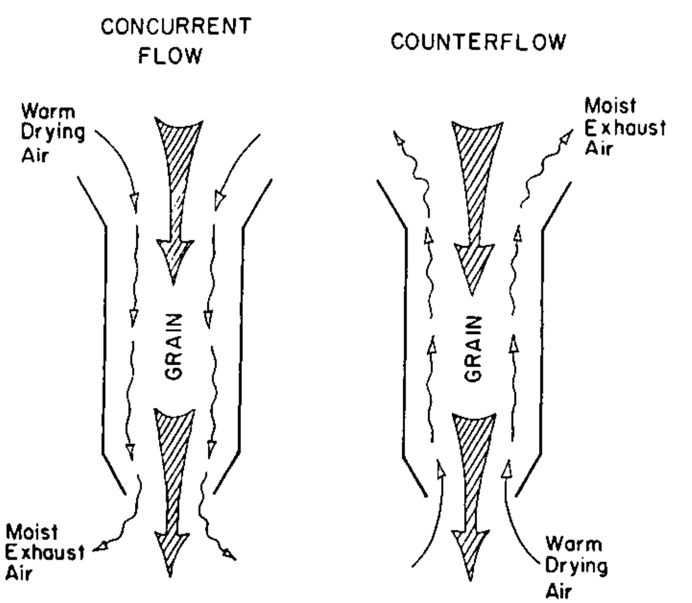

Figure 9-14. Concurrent-flow and counterflow grain-drying systems.

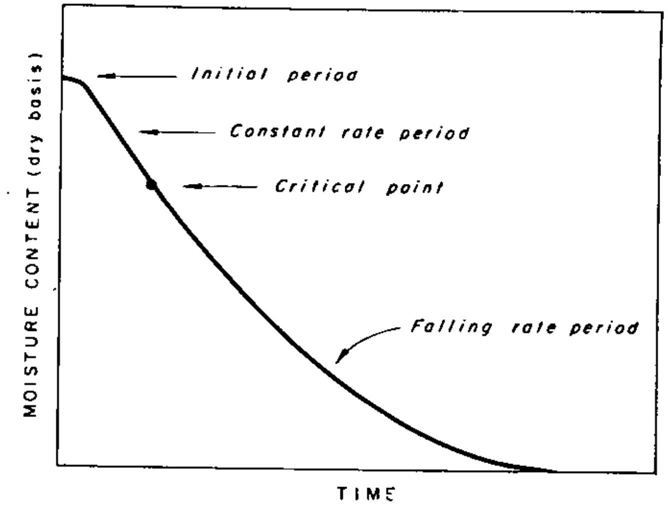

Figure 9-15. Drying rate periods.

Individual kernel drying

The drying of a solid material involves the simultaneous processes of heat and mass transfer. During the drying of rice, air is used to convey heat to the grain and take moisture away from it. Heat is required to evaporate moisture from the kernel. Mass transfer of water occurs within the kernel as well as on the grain surface.

Drying can be divided into three periods (Fig. 9-15): initial, constant rate, and falling rate. In the constant rate period, the quantity of water removed per unit time per unit quantity of dry matter is constant. This pattern may occur in high-moisture foods where the product surface will remain saturated with water. Rice may exhibit a constant rate period if it is very wet at the onset of drying. Such conditions could prevail if rice is harvested after rain or heavy dew. In the falling-rate drying period, the quantity of water removed per unit time per unit quantity of dry matter is not constant. In this case, the product surface is no longer water-saturated, and the rate of drying is governed by the movement of internal moisture. The initial period, which is short and occurs at the start of drying, should be considered as a kind of warmup time. In the constant-rate period, the mathematical derivative of moisture content in relation to time is constant. This derivative steadily decreases during the falling-rate period. The moisture content which makes the change from the constant-rate to the falling-rate period is generally referred to as the "critical point."

The drying of a rice kernel occurs principally in the falling-rate period. The inner movement of moisture within a grain kernel during the falling-rate period controls the drying process. The internal moisture movement is a complex phenomenon that is not clearly understood. Hall (1957) listed the following physical mechanisms as possibilities in controlling the transfer of moisture within agricultural products:

1. diffusion (liquid or vapor)
2. capillary action
3. shrinkage and vapor pressure gradients
4. gravity
5. vaporization of moisture

In their studies with rice, Yamazawa et al. (1971) found capillarity to be the principal mechanism of moisture transfer between the hull and kernel during the initial stage of drying. They also discovered that moisture was transferred by vapor diffusion through the gap between the hull and the kernel. It is generally accepted that moisture movement in a grain kernel is a diffusion (liquid or vapor) process.

Brooker et al. (1974) and Henderson and Perry (1976) have discussed the shortcoming of the theoretical diffusion-type approach in grain drying. The problems are centered around the simplifying assumptions made in the development of diffusion models. These simplifications have introduced significant error into the theoretical diffusion analysis. Thus, most of the drying equations that have appeared in the literature over the years are of an empirical nature.

Thin-layer drying

One approach in analyzing grain drying is considering thin-layer drying. The term "thin layer" refers to a bed of grain that is approximately one kernel deep. Many empirical studies have been conducted using thin layers of grain to examine the drying behavior of the particular product in question. Data are collected specifying the quantity of moisture removed from the grain as a function of time when dried with air having certain psychrometric properties such as temperature and relative humidity. When thin beds of grain are dried with air at different conditions, the resulting data can be treated to yield an equation that specifies moisture removal as a function of time and air properties. The equation may take various forms and is accurate within a specific range of drying air velocities, air temperatures, relative humidities, and grain moisture contents.

Many thin-layer drying simulation models have been developed in the past 15 years. Due to the availability of computers, complex mathematical equations have been used to simulate drying processes. Gunasekaran (1986) has reviewed many of these simulation models.

Many authors have discussed Newton's law of cooling in reference to the thin-layer drying behavior of small grains. Newton's law states that the rate of change of temperature of a body is proportional to the temperature difference between the body and the surrounding medium. The analogy of drying to heat transfer is made by substituting a moisture content difference for a temperature difference. Thus, moisture instead of temperature would be the driving force. The drying equation obtained from the Newton analogy would be

$$\frac{dM}{dt} = -k(M - M_e) \tag{4}$$

Integration yields

$$\frac{M - M_e}{M_o - M_e} = K \exp(-kt) \tag{5}$$

where

dM/dt = drying rate
M_o = initial moisture content at time 0 (% MCdb)
M = moisture content at time t (% MCdb)
M_e = equilibrium moisture content (% MCdb)
t = time (h)
k = drying rate constant (h^{-1})
K = constant of integration

The drying equation (4) was used by Kachru et al. (1970) to analyze the thin-layer drying of four rice varieties. They found a close relation between this equation and the drying rate of paddy rice. The authors also concluded that the drying rate constant k was a characteristic of the paddy and not a function of the drying rate or grain moisture content. The drying rate constants determined for the varieties of paddy rice considered were IR8: $k = 0.6504\ h^{-1}$; Dular: $k = 0.8040\ h^{-1}$; Patnai-23: $k = 0.8424\ h^{-1}$; and Taichung Native 1: $k = 0.6480\ h^{-1}$. Henderson and Pabis (1961) also applied a Newton-type equation and studied the effect of temperature on the drying rate constant k. They concluded that k was related to temperature by an Arrhenius-type equation stating that $\ln k$ is proportional to the negative inverse of the absolute temperature.

The Newton-type drying equation has also been discussed by Allen (1960) with regard to shallow-bed drying (1.9-cm-thin layer) of rice. He found from experimental work that modifications and restrictions would be necessary before the equation could be applied to the drying of rice. He concluded that moisture content and the drying rate constant are functions of the drying air temperature, drying air humidity, the quantity of drying air supplied, and the initial and instantaneous values of the grain moisture content. Due to this variability in M_e and k, he suggests that the first drying period (up to 1/2 h) be given a treatment different from the latter drying period. The Newton-type equation was applied to each drying period but with different values of k and M_e.

A number of equations describing the thin-layer drying of rice can be found in existing technical literature. Henderson and Henderson (1968) presented the following equation to describe the drying history of rice (Colusa 1600) when the drying was carried out with air at 41.7°C (107°F):

$$\frac{M - M_e}{M_o - M_e} = 0.650\,[\exp(-0.220\,t) + \tfrac{1}{9}(-0.220(9)\,t)] \qquad (6)$$

During thin-layer rice drying studies, relative humidity from 3 to 60%, air velocity from 0.025 to 0.5 $m^3/s.m^2$ and air temperature from 35 to 75°C were used by Verma et al. (1985). They found that the drying rate is independent of the relative humidity of the drying air and only slightly affected by air velocity. Air temperature was the main factor in controlling the drying rate. Based on this result, Noomhorm and Verma (1986) proposed a generalized single-layer rice drying model. Their model is valid for thin-layer drying of rice in a one-pass drying operation.

In multipass commercial drying operations, rice is exposed to heated air for less than 40 min for each pass. Wang (1978) experimentally determined a thin-layer dry equation for medium-grain rough rice at 30 to 55°C and 15 to 95% RH conditions. He found that the diffusion model was not suitable for drying time of less than 40 min. He suggested the following thin-layer drying equation at various air temperatures and humidities (Wang and Singh 1978).

$$\frac{M - M_e}{M_o - M_e} = \exp(-P\,t^P) \qquad (7)$$

where

t = time, minute
$P = 0.01579 + 0.0001746\,T - 0.01413$ RH
$Q = 0.65450 + 0.0024250\,T + 0.07867$ RH
T = temperature, °C
RH = relative humidity
M = moisture content, dry basis

There is no universally accepted equation to describe thin-layer drying of rice. The reason for this is that the drying characteristics of rice may vary with types of rice (short, medium, or long grain), its variety, previous grain history, and drying environment.

Deep-bed drying

A deep-bed drier may be defined as one in which there is a finite moisture gradient through the drying layer at any time except time 0 (Henderson and Perry 1976). Deep-bed drying occurs in all situations where the drying bed is more than thin-layer deep. All fixed-bed and continuous-flow driers are of the deep-bed type.

Thin-layer drying models could be used to simulate deep-bed drying processes. The drying rate simulation of a deep-bed drier has been performed by dimensional analysis (Nelson 1960; Kachru and Matthes 1976), experimental models and graphical approach (Hukill 1954), and computers.

Computer modeling of rice-drying operation was evaluated in the late 1970s and early 1980s by many researchers. In most cases, simulation of heat and mass transfer equations were used to find the solutions of the diffusion law for spheres or infinite cylinders (Aguerre et al. 1982; Steffe and Singh 1982; Hendrickx et al. 1986).

Drying simulation models are valuable as an aid in obtaining optimum drier design and for increasing our basic understanding of the drying process. Insight into the drying behavior of a bed of rice can be gained by looking at the results of a fixed-bed drier simulation (Fig. 9-16). Simulation models can also be used to predict drier performance. Some driers use computer controls which allow careful monitoring and controlling of process parameters. Online simulation and optimization procedures are used (Nybrant and Regner, 1985). Singh et al. (1978) presented a numerical approach to simulate rice drying and predicted moisture content, head yield, and energy consumption of a cross-flow rice drier.

Energy consumption during drying operations is a very important factor in designing and operating a rice drier. Gunasekaran (1986) gave a detailed review of several grain-drying systems and optimal energy management procedures.

RICE CRACKING

Suncracks, fissures, and checks are some of the names given to the cracks always found in rice. The word "suncrack" is a misnomer because it implies that cracking is simply the result of sun-drying. Although sun-

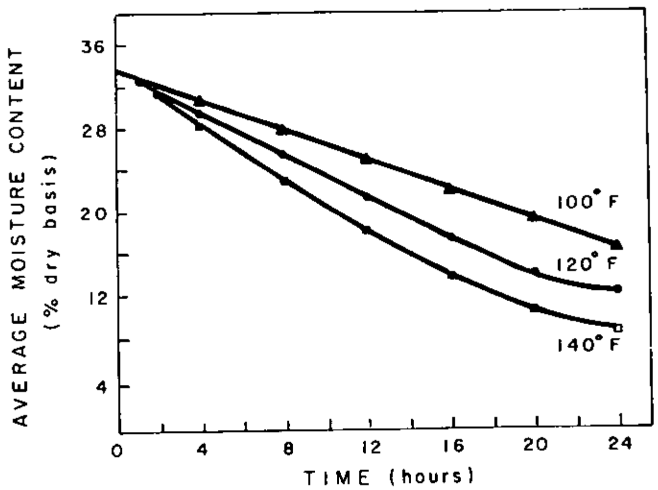

Figure 9-16. Relationship between rice moisture content and bed position.

drying is an important factor that causes field cracking, there are many other factors which cannot be ignored. This is particularly true when rice is commercially dried because it is removed from the field when it still has a high moisture content. In this case, mechanical drying and not natural sun-drying is the contributing factor.

Rice cracking structurally weakens the kernel, making it more susceptible to breakage during milling and handling operations. The economic consequences of this are significant because the value of broken rice is much less (1/3–1/2) than that of whole rice. Cracked rice is also more susceptible to insect infestation. Cracking has the added limitation that it may reduce the vitality of the seed rice. Cracks that occur across the kernel, as most cracks do, may reduce seedling vigor by decreasing endosperm availability.

The mechanism of rice cracking has been studied by a number of researchers. Henderson (1954), in his studies with short-grain rice concluded that cracking during fast drying was due to an increase in temperature rather than a decrease in moisture in portions near the surface of the kernel. He found that cracking could also be caused by a rapid increase in moisture which could occur in the field if dew accumulated on the kernels. Kunze and Hall (1965) found that cracking occurred when brown rice, equilibrated at a particular humidity, was subjected to a high-humidity environment. The degree of cracking was dependent on the magnitude of change in relative humidity. The researchers hypothesized that adsorptive

fissures were caused when external cells expanded by adsorbing moisture and produced compressive stresses in surface layers. The internal parts of the kernel would resist these stresses and fail if the material tensile strength was exceeded.

Rhind (1962) mentions that moisture changes in rice result in unequal volumetric changes that induce internal stresses. He reports that the highest tensile stresses can be expected in the surface layers during drying and in the inner grain parts during adsorption. A similar conclusion has also been reached by Nayato et al. (1964) and Kunze and Choudhury (1972). They found that cracking from hydration and drying was due to unequal swelling or shrinking within the rice kernel. The force distribution within a rice kernel was more fully explored in a hypothetical two-dimensional stress analysis presented by Kunze and Choudhury (1972).

Rhind (1962) suggests that a change in the physical behavior of rice starch occurs at 15% MCwb, and this change of state is a factor in the cracking phenomenon. MacDonald (1967) has suggested that a physical change within the rice kernel may also be a factor that contributes to rice cracking. This author observed that cracks usually occur between the cell walls of the endosperm and rarely pass through them. He hypothesized that it is not the cell walls which fail when overstressed but the gum holding the walls together. MacDonald (1967) also mentions that the intercellular gums are somewhat plastic above 21% MCwb and become increasingly inelastic with lower moisture contents.

Ban (1971) found that rice cracked after high rate of drying, not during drying. He suggested that the head yield should not be determined until 48 h after drying. Kunze (1979) and Sharma and Kunze (1982) confirmed this finding. They hypothesized that moisture gradient after drying caused the cracking. Cracking continued until the moisture gradient disappeared across the grain. Higher tempering temperature can increase moisture diffusion and reduce the moisture gradient. Lower breakage was found by Wasserman et al. (1964) and Steffe and Singh (1980) when higher temperature was used during tempering stages.

Rice cracking may occur in the field, during drying, storage, milling, or handling. Kunze and Parsad (1976) considered situations where moisture-adsorbing environments may occur which can cause rice cracking. They suggest that harvested rice may have grains sufficiently dry that they will fissure when subjected to an environment conducive to the adsorption of moisture. The researchers specified two situations where the low moisture rice in harvested grain may experience a moisture-adsorbing environment: (1) in the combine hopper or holding tanks before drying, and (2) in a drier where the drying air has become highly humidified before reaching the grain.

In his review of rice-drying researchers, Mossman (1986) indicated that drying temperature has been shown to have no effect on rice breakage if the rate of drying is held to a minimum.

A number of authors have made recommendations to reduce cracking. Itoh et al. (1974) found that rice temperature at exit of the drier was closely related to the number of checked kernels; the authors suggested 35°C (95°F) as a safe limit for rice temperature during drying. Arora et al. (1973) recommend that a temperature difference larger than 43°C (109.4°F) between rice and the drying air temperature may result in serious cracking and suggest that the drying air temperature be kept below 53°C (127.4°F). Henderson (1954) has advised that the following steps should be taken to minimize thermal strain, minimize cracking, and achieve the highest head yields: (1) harvest at a high moisture content, (2) dry at as low an air temperature as possible, and (3) use as many passes as convenient in multipass continuous-flow drying. Nguyen and Kunze (1984) found that rice stored at 10% RH and 45°C temperature had less cracking after rapid drying.

RICE STORAGE

A commercial bulk storage system designed for long-term safe storage of rough rice must (1) provide proper aeration to prevent spontaneous heating, and (2) maintain the rice grain at low moisture content to protect it from fungi and insects. Cogburn (1985) summarized control methods for fungi, insects, rodents, and birds for the storage of rough rice. Rough rice can be stored up to 5 years at 12% MCwb in Texas (Calderwood et al. 1984), but only 2 to 3 months at 14% MCwb (Wimberly 1983).

The operation of aeration systems for bulk storage in high-humidity environments calls for the operator's constant care and attention. The following discussion is aimed at developing engineering parameters for the design and selection of an aeration system for storing rough rice.

Storage structures, usually classified as "flat" or "vertical," are used to store rice for long durations. Flat storage refers to a structure with height less than the width or diameter, whereas vertical storage entails height greater than width or diameter. Vertical storage has the advantage of easy unloading by gravity via hopper bottoms. Mechanical means, such as power shovels or sweep augers, are needed to unload flat bins.

Respiration of rice grain must be taken into account when designing storage systems. Since rice is a biological product, some deterioration will occur during storage, even if the rice is stored at the 13.5% "safe" moisture content.

Aerobic respiration, requiring atmospheric oxygen, can be expressed as

$$C_6H_{12}O_6 \rightarrow 6CO_2 + 6H_2O + 673 \text{ KCal.} \qquad (8)$$

The respiration process as expressed by Eq. (8) involves the utilization of oxygen, evolution of carbon dioxide, liberation of thermal energy, and decrease in weight. The spontaneous generation of heat is of serious consequence in bulk storage, since rice has a porous, granular structure and low thermal conductivity. If no convective currents are present, the grain mass practically insulates itself. Thus, respiration could lead to heat-damaged grain if proper care is not taken.

Cogburn et al. (1983) states that higher temperature during storage causes moisture migration, and recondensation at the surface of the rice bed creates a zone of wet rice. The combination of heat and moisture produces ideal conditions for fungi growth, and results in discolored grains. Gras et al. (1989) conducted a quantitative study of the rate of yellowing. He concluded that the storage temperature was far more significant for the yellowing of rice than the concentration of oxygen in the storage atmosphere, or even the moisture content of the stored grain. The results were consistent with nonenzymic browning as the mechanism of yellowing (such as caused by fungi).

An aeration system for storage, if provided, has several advantages including (1) equal storage temperatures, thus avoiding the occurrence of hot spots, (2) cooling of rice (depending on the weather), thus minimizing insect activity and mold growth, (3) removal of odors from stored rice, and (4) distribution of fumigants inside the stored product.

Schroeder and Calderwood (1972) recommend that aeration for cooling dry rice during the winter months or for equalizing temperatures during other months can be accomplished with airflow rates as low as 1.3×10^{-6} $m^3/s \cdot kg$. Although typical airflow rates for aeration range between 1.0×10^{-6} to 2.1×10^{-6} $m^3/s \cdot kg$, a higher airflow rate is needed to prevent spontaneous heating.

An excellent discussion on aeration-system design is given by Holman (1960). In the following discussion, a summary of Holman's recommendations, applicable to designing aeration systems for rice, is presented.

The grain must be adequately cooled during storage to prevent mold growth and insect activity. Typically, during late summer and fall harvest, rice dried with heated air may go into storage with grain temperature up to 37.8°C (100°F). Although there is no one optimum storage temperature, mold growth is inhibited below 21.1°C (70°F) (for rice at 13% MCwb). Insect activity is considerably reduced at temperature below 15.6°C (60°F).

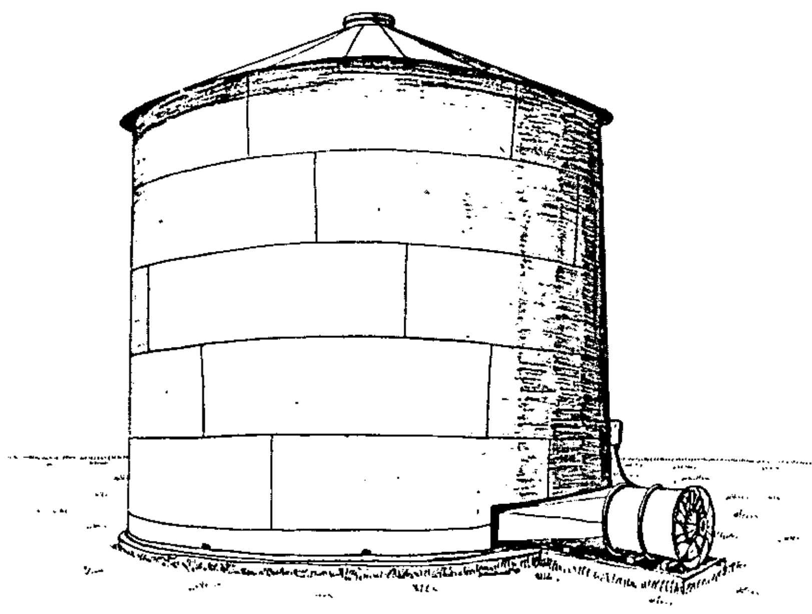

Figure 9-17. Fixed fan for each storage.

It should be emphasized that aeration will not entirely replace fumigation as a means of insect control.

The selection of aeration systems for rice requires consideration of (1) type of storage structure in which the aeration system is to be installed, (2) airflow rate (e.g., $m^3/s{\cdot}kg$), and (3) number of storage structures and quantity of grain to be aerated. Based strictly on the above information, the following should be determined: (1) total air volume to be supplied, (2) static pressure against which the fan must operate, (3) size and type of fan and motor, and (4) size of ducts and supply pipes.

Types of Aeration Systems

Satisfactory aeration of grain in upright and flat storage can be accomplished through the following arrangements of fans and ducts.

A fixed fan for each storage or for each duct in the storage is simple and efficient, as shown in Fig. 9-17. The disadvantage of the system is its high cost since several fans and motors are required. In addition, fumigants must be introduced into each individual fan.

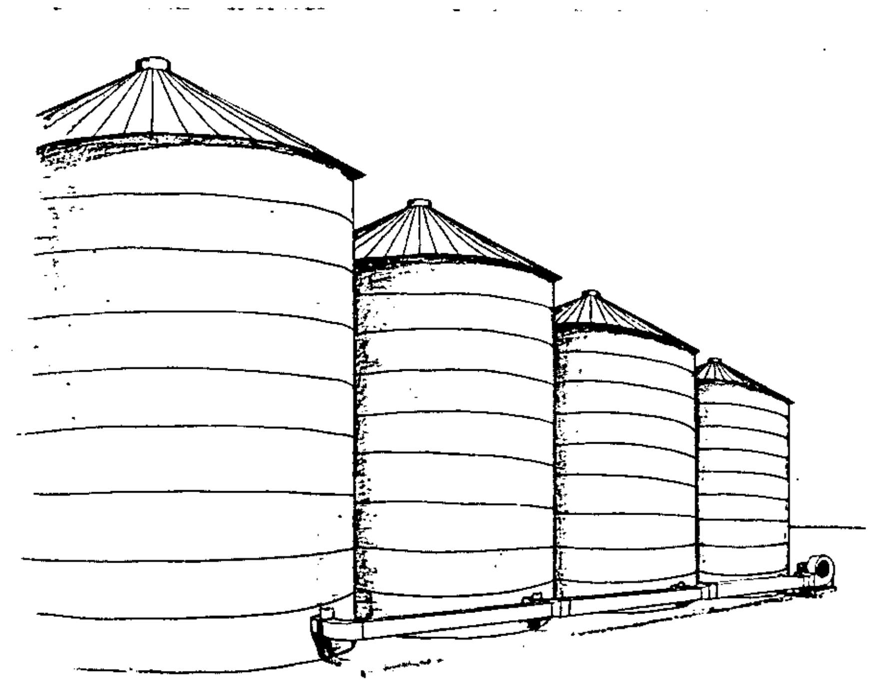

Figure 9-18. Manifold system for several storage structures.

A manifold system consists of one fixed fan connected to several storages or ducts with one manifold, as shown in Fig. 9-18. This type of system is less expensive. The use of dampers allows aerating one or several storages at the same time. In designing such a system, friction losses in the manifold and pressure losses in the bends and dampers must be considered. The manifold systems are usually poor air distributors.

A relatively cheaper system uses a portable fan to aerate several storages. In such a system, the fan and motor are mounted on wheels and moved to an adjoining storage space when aeration of one is complete.

An airflow rate of 1.3×10^{-6} $m^3/s{\cdot}kg$ is suitable for purposes of cooling dry rice during winter months or for equalizing temperatures in the storage unit during other months. A higher airflow rate is needed to prevent spontaneous heating for undried rice. In addition, higher airflow rates are required when the aeration system is used for supplementary drying by cooling rice after a drier pass. In selecting an airflow rate, proper consideration must be given to the lowest rate that can be permitted in any portion of the stored grain.

The lowest airflow rate in a well-designed aeration system for upright storage is usually not less than 90% of the selected rate. However, in flat storage, the lowest airflow rate may be only 1/2 or less of the selected rate. This emphasizes the importance of considering the lowest airflow rate when designing aeration systems.

Fan Selection

The following parameters are important in the selection of fans for an aeration system: (1) the volume of air to be moved, (2) the static pressure at which the fan must operate, and (3) the noise level of the fan. The factors influencing static pressure include airflow rate, grain depth, variety (such as rough hulled or smooth hulled), and size of the grain. The fan speed influences the noise.

Both propeller (axial flow) fans and centrifugal (radial flow) fans are used for aeration where the static pressure of the grain and system is less than 10 cm of water. Centrifugal fans are used to obtain higher pressures.

A "forward-curve" centrifugal fan, consisting of a large number of blades, operates at a relatively low speed. The motor in this fan may overload if the static pressure is decreased. A centrifugal fan with straight blades also overloads when static pressure is reduced. A "backward-curve" centrifugal fan is a high-speed fan. It is more efficient but more expensive than the previously described centrifugal fans. Operating backward-curve centrifugal fans near the point of greatest efficiency will avoid the danger of overloading the motor.

The performance of the aeration system can be seriously affected if the fan is not properly connected. Short elbows at fan inlet and exit restrict the fan output. It is important to keep the pipe size uniform.

Duct Design and Selection

Semicircular and inverted V-shaped perforated ducts are most common. Perforated false floors are relatively expensive. In perforated ducts the area of the perforations should equal at least 10% of the total duct surface area.

The following three dimensions are important in designing a duct system. (1) Both the cross-sectional area and length of the duct influence the uniformity of airflow and air velocity within the duct. (2) The circumference of the duct influences static pressure losses in grain surrounding the duct. (3) The distance between the ducts influences the uniformity of airflow through the grain between ducts.

The duct cross-sectional area can be determined by the following:

$$\text{cross-sectional area, m}^2 = \frac{\text{total air volume (m}^3\text{/s)}}{\text{air velocity (m/s)}} \quad (9)$$

Table 9-1. Recommended Maximum Allowable Air Velocities within Ducts Installed in Flat Storages

Airflow Rate Per m³ of Product	Corn, Soybeans, and Other Large Grains — *Air Velocity Within Ducts (m/s) for Grain Depths of* 3.05 m	6.1 m	9.14 m	12.19 m	15.24 m
$m^3/s \times 10^4$	m/s	m/s	m/s	m/s	m/s
6.70	—	5.08	7.62	8.89	10.16
13.40	3.81	7.62	10.16	—	—
26.79	5.08	10.16	—	—	—

Source: Holman (1960).

An air velocity of 10.16 m/s/min is permissible for vertical storages. The maximum recommended air velocities in ducts for flat storage are given in Table 9-1.

Excessive pressure losses in grain surrounding the duct can be avoided by limiting the velocity of air entering or leaving the grain. It is obvious that this velocity will be influenced by both the surface area of the duct and the airflow rate.

For upright storages, the duct surface area should be selected to limit the air velocity through the grain near the duct to 0.15 m/s or less. For flat storage, the air velocity through the grain near the duct should be limited to 0.1 m/s by selection of the proper duct surface area.

A maximum velocity of 12.7 m/s is permissible in supply pipes that provide for the passage of air between the duct and the fan.

Fan Horsepower and Static Pressure Requirement

The information for determining fan horsepower and static pressure requirements can be obtained from Fig. 9-19. This figure is drawn from data by Shedd (1953) for long-grain rice. Since Shedd's data on basic pressure drops are for loose-fill rice, the values were increased by 40% to account for packing. In addition, a total of 2.54 cm static pressure was added to all values to account for radial pressure drop through the rice immediately surrounding the perforated duct and friction in the supply pipe and other components of the system. The fan horsepower was computed assuming 62.8% static efficiency. The following formula was used:

$$\text{HP} = \frac{\text{static pressure (Pa of water)} \times \text{m}^3\text{/s}}{34{,}065} \quad (10)$$

As an illustration, for a 6.1-m depth of rice, the airflow rate is 1.04×10^{-5} $m^3/s{\cdot}kg$. The fan power requirement is 1.0 HP.

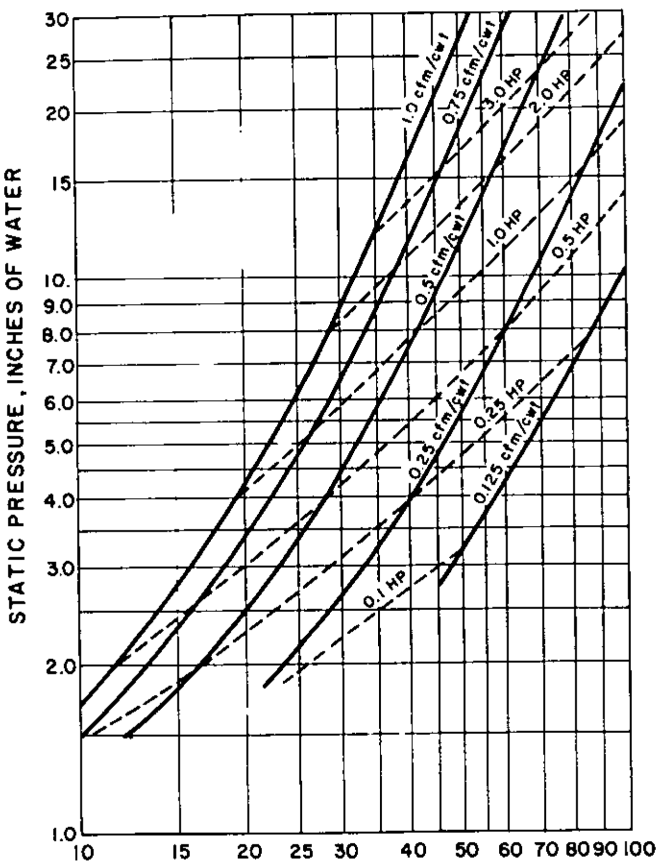

Figure 9-19. Static pressure and fan horsepower required for aerating rough rice (long grain, Blue Bonnet) at different rates of airflow and at depths from 10 to 100 ft (consult Appendix for appropriate table on metric conversions).

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10

Milling

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The *purpose of rice milling is to* remove the hulls and bran from harvested, dried rough rice and to produce a milled, polished, or white rice. The meaning of the term milling varies appreciably, *not only in the many different* industries in which the term is used, but also within the grain industry. In the rice industry, *milling can refer either to the overall* operations in a rice mill—cleaning, shelling, bran removal, size separation, etc.—or it can refer simply to the one operation of removing of the *bran or outer layers from the* brown rice to produce a whole grain white rice product.

The following terminology is also somewhat specific to the rice industry; clarification at this point may help to understand better the discussions on rice milling in this chapter. Rough rice, which is also known as paddy rice, is the harvested, unshelled rice as it comes from the field. Shelling refers to the removal of the outer shell. The operation is conducted in machines known by many different names such as shellers, hullers, huskers, dehuskers, and decorticators. Similarly, the shells are also known as hulls, husks, and chaff.

In most parts of the United States, the term hulling has the same meaning as shelling; however, in some areas of the United States and other countries hulling also refers to the removal of both hulls and bran. This *probably stems* from the fact that earlier machines such as the Engelberg Huller removed either the bran or both hulls and bran in one operation. After removal of the hulls, the rice is called brown rice. This terminology does not refer necessarily to the color of the rice but simply infers that the bran has not been removed. The brown rice is also known as shelled rice, husked rice, cargo rice, and loonzian (Houston and Kohler 1970). The brown rice is milled in a milling machine whereby all or most of the bran is removed to produce the white milled rice. The term bran includes the soft germ and several histologically identifiable soft layers surrounding the hard starchy endosperm. This milling operation to remove the bran is sometimes called scouring or whitening. In polishing the milled rice, traces of bran that may remain on the rice after milling are removed and the rice surface is given a smoother finish. Total milled rice includes both the head rice and the broken rice. Head rice or head yield refers to the milled whole rice grains (unbroken kernels and broken kernels which are at least *three-fourths of an unbroken kernel*). The *broken rice* (kernels which are less than three-fourths of an unbroken kernel) is generally subdivided into three sizes—second heads, which are the largest of the broken kernels; screenings, which have an intermediate size; and brewers rice, consisting of the small broken kernels. It should also be understood that, in the rice industry, a rice mill performs a series of processing operations which, in general, include cleaning, shelling, milling, polishing, separation of whole and broken rice, sizing of broken rice, packaging, and several auxiliary operations such as husk aspiration, paddy separation, *bran processing, and rice coating.*

Milling is of great economic importance to the rice industry, particularly since broken rice is worth about half as much as whole rice. The objective of these rice mill operations is to produce a white, whole grain or head rice product that is essentially free of bran and foreign matter and which contains a minimum of broken kernels.

In this chapter emphasis will be placed in the following related areas of rice milling. A brief review of the early milling equipment and a description of current milling equipment will be presented. Factors that affect rice breakage will be discussed such as the condition of paddy rice, harvesting, drying, handling, and milling machine settings. The advantages and disadvantages of lightly milled rice as related to legal requirements, nutrition, and cooking characteristics will be presented. Deep milled rice and the production of high protein flour, techniques for measuring degree of milling and the process for solvent extractive *milling*—its products and advantages and disadvantages—will also be included in this discussion.

RICE-PROCESSING MACHINERY

In some rice-growing areas, milling is accomplished by very primitive methods such as pounding the rough rice in a wooden mortar and pestle

followed by winnowing. At the other extreme are very modern methods where milling is accomplished in large, highly automated plants with the manifold operations being monitored from a central console (Tolson and Robe 1977). Thus, there is no typical rice mill. In addition, rice-processing equipment is manufactured in a number of countries throughout the world with minor to major differences in the design of individual pieces of machinery. However, the modern processing of rice consists of essentially the same steps: (1) cleaning the incoming rough rice, (2) shelling the rough rice, (3) milling to remove the bran from the brown rice, (4) *sizing the* milled rice by length into whole grain and different sizes of brokens, (5) mixing milled whole grain and brokens to meet specifications of buyers, and (6) packaging. Other descriptions of rice milling equipment include those by Witte (1970, 1972) and Van Ruiten (1976, 1985).

Cleaning

Dried rough rice is first cleaned to remove foreign material such as straw, soil particles, and weed seeds. Cleaning is an important step in producing a high quality milled rice. According to USDA standards (USDA 1976), the highest grade (U.S. no. 1) of milled rice has a maximum limit of one weed seed in 500 g. If the milled rice contains two weed seeds in 500 g, the rice is downgraded to a U.S. no. 2 rice, even if all other specifications of no. 1 rice are met. Separation of foreign matter is based on differences in gross size, weight or density, and shape (principally length) of the impurities compared to the rough rice.

Figure 10-1 shows in cross section a scalping machine (scalperator) which removes straw and other large objects by screening and dust and light weight material by aspiration. Rough rice enters through hopper (1). The feed rate is regulated by the gate (2). The rice falls on the rotating cylindrical screen or scalping reel (4). The mesh size of the screen is such that straw, sticks, and other large foreign matter are carried over the screen to discharge (13), *while the rice falls through the screen.* The rice is then subjected to a stream of air which removes low-density matter such as dust, sterile florets, and stemmers and discharges these in settling chamber (8).

Flat inclined screens (screen separators) having a horizontal reciprocating motion may be used to clean the rice further. The separating action of screens is based on length of the objects to be separated. A roughly spherical weed seed having a diameter equivalent to the width of a rough rice kernel may fall through the round perforations of a screen; the rough rice laying flat on the screen will not pass through because *its length is* longer than the diameter of the perforations. The rough rice thus bridges across the perforations in its movement down the inclined screen. In the

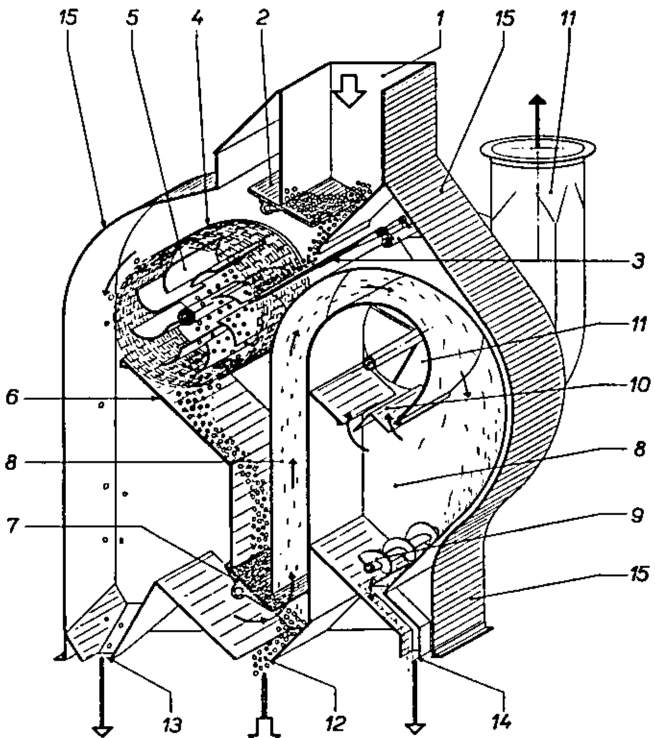

Figure 10-1. Scalping machine (scalperator). (1) Feed hopper. (2) Feed regulation gate. (3) Adjustable rack. (4) Wire mesh scalping reel. (5) Baffle plates. (6) Grain receiving rack. (7) Seal gate. (8) Aspirating leg and settling chamber. (9) Screening screw conveyer. (10) Air outlet baffle plates. (11) Suction fan. (12) Grain outlet. (13) Scalping outlet. (14) Screenings outlet. (15) Machine frame and housing. Courtesy of Food and Agriculture Organization of the United Nations (Borasio and Garibaldi 1957).

same fashion sticks or straw longer than the rough rice may be separated by passage over a slotted screen. Indented disk separators may also be used to separate rough rice from longer or shorter impurities. The operation of indented disks is discussed in more detail in connection with the separation of whole grain milled rice from broken pieces. Permanent or electromagnets are generally installed in the stream of rice to remove ferrous metals. Stoners may also be included to remove dense materials. These machines essentially operate by aspirating the rough rice away from the denser objects.

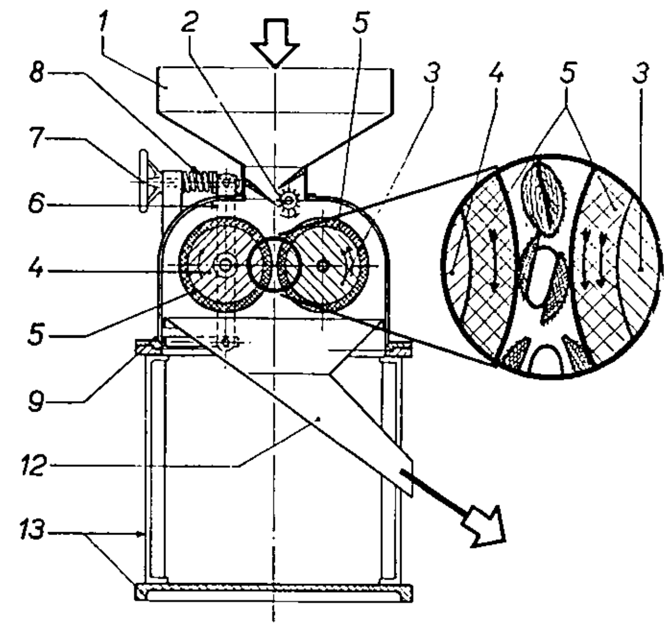

Figure 10-2. Rubber roll sheller. (1) Feed hopper. (2) Feed roller. (3) Fast roll. (4) Slow roll. (5) Rubber surface. (6) Roll shifting arm. (7) Roll clearance adjustment. (8) Roll tension spring. (9) Husker housing. (12) Husked rice and husk outlet. (13) Machine base and frame. Courtesy of Food and Agriculture Organization of the United Nations (Borasio and Garibaldi 1957).

Shelling

The next step is to remove the hulls (shelling). In Fig. 10-2, a cross-sectional side view of a modern rubber roll sheller is illustrated. The feeder (2) meters a falling stream of rough rice between two closely spaced rubber rollers that are turning in opposite directions and at different speeds. As the rice passes between the rollers it is subjected to a shearing force that separates the two hulls (glumes) from the brown rice, as shown in the exploded view on the right of Fig. 10-2. The distance between the rollers may be regulated by a handwheel (7), as illustrated, or, in the most modern machines, by a pneumatic mechanism that automatically separates the rolls and turns off the driving motor if the rice flow through the machine is interrupted. Excessive pressure can cause excessive breakage of the grain. The main disadvantage of this type of sheller is that the rollers wear rapidly and must be replaced or have the surfaces renewed quite frequently, particularly in hot weather. However, the efficiency of the rubber roll sheller in shelling grain of widely varying thickness more than offsets the expense of the rollers. Prior to the introduction of the rubber roll sheller an earlier design called a stone sheller or under-runner disk sheller was used. This sheller is discussed in detail by Garibaldi (1974). The stone sheller has the disadvantages of being dependent on a uniform length of the grain to be shelled, breaking more grain than the rubber roll sheller, and abrading the bran on the brown rice. However, the disk sheller is still very commonly used in developing countries and has the advantage that the abrasive surfaces of the machine can be repaired by the miller himself using a mixture of emery or silicon carbide and an appropriate cementing compound. Centrifugal or impact shellers are also available (Masumoto 1989).

The product of the sheller is a mixture of whole grain brown rice, broken brown rice, unshelled rough rice and hulls. The hulls, which have a large surface area for their weight, are removed from the mixture by aspiration. The remaining mixture of brown and rough rice is conveyed to a paddy machine (paddy separator).

Paddy Separators

The paddy machine separates the brown and rough rice received from the aspirator. There are two types of paddy machines in general use. The compartment type is illustrated in Fig. 10-3. The upper diagram shows a top view of the separator which has a horizontal reciprocating motion in the plane of the paper in the directions of arrow A. The table (1) is divided into compartments (2) extending crosswise to the direction of motion. Each compartment has zig-zag sides and a smooth steel bottom slightly inclined with the higher side being on the left. The grains slide from side to side of the compartment. The lower density rough rice stratifies as a layer above the brown rice. The oblique sides of the compartment tend to impart an upward thrust to all the grains. However, the greater density of the brown rice causes it to slide down the incline and be discharged into the collecting trough (5) while the rough rice is discharged at the top of the incline into collecting trough (4). The lower diagram of Fig. 10-3 is a cross-sectional view with the direction of motion being perpendicular to the plane of the paper. The stroke length, frequency of strokes, and the inclination of the table may be adjusted to achieve the separation. The feed to each compartment is adjustable by feed gates so that each compartment receives the same amount of rice. The table may have a number of tiers (usually three to five). The collecting troughs may be inclined in various

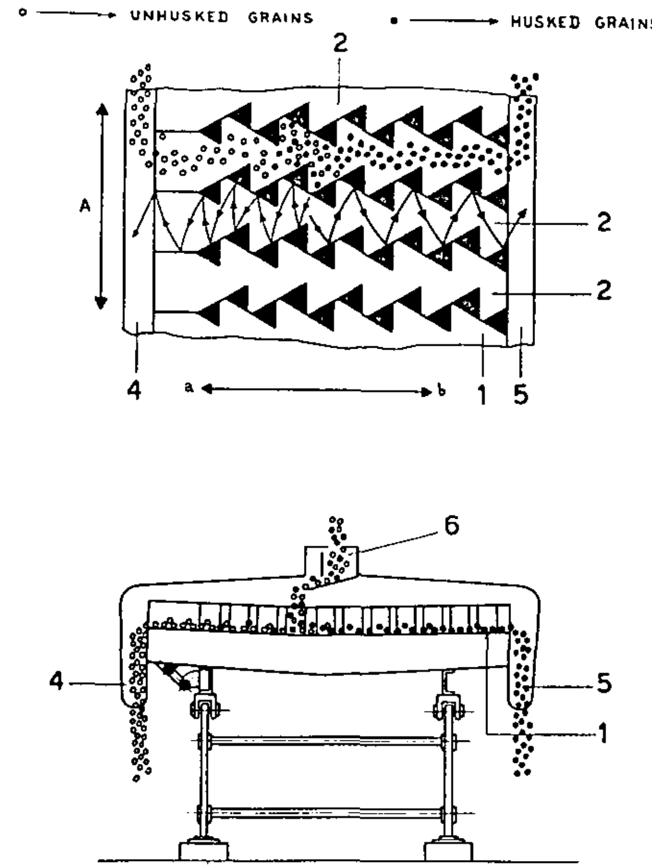

Figure 10-3. Compartment separator-type paddy machine. (1) Table (arrow shows *direction of motion of table*). (2) *Compartments*. (3) *Triangular raised* portions of table (in solid black). (4) Unhusked grain outlet. (5) Husked grain outlet. (6) Intake hopper. Courtesy of Food and Agriculture Organization of the United Nations (Garibaldi 1975).

ways so that the discharge may be at either end or at the middle of the machine to suit space requirements in the mill.

A more recent Japanese design of a paddy machine is called an oscillating tray or gravity-type separator (Fig. 10-4). Briefly, this machine consists of several tiers of indented steel trays (3) inclined at an angle. The mixture of brown and rough rice (1) from the sheller is introduced at the top of the tray. The tray oscillates with an upward and forward motion toward the top of the incline. The kernels of rice bounce up and down on the trays

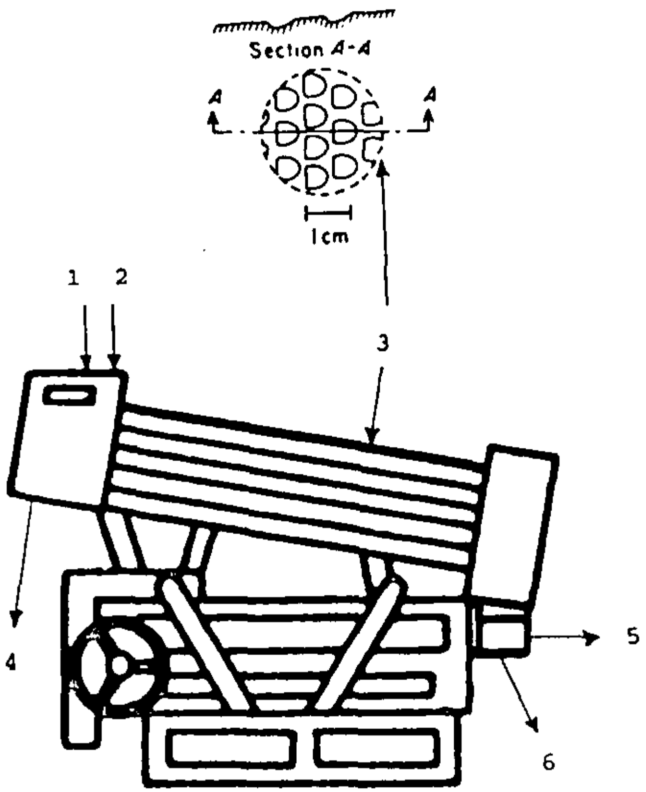

Figure 10-4. Oscillating tray-type paddy separator. (1) Feed from sheller. (2) Recycle stream. (3) Tray surface. (4) Brown rice discharge. (5) Paddy rice discharge. (6) Mixture of brown and paddy rice for recycle.

which impart an upward motion to the denser brown rice while the rough rice tends to slide over the brown rice and down the incline. This machine discharges three streams of material: pure brown rice (4), pure rough rice (5), and a mixture of brown and rough rice (6) which is recycled through the machine (2) to achieve a complete separation. Das (1986) analyzed in detail the operation of the tray-type separator.

Commercial machines are large and expensive and are not suitable for laboratory use. Kunze et al. (1989) developed an inexpensive laboratory size paddy separator.

The rough rice from the paddy machine is sent back to the shelling machines or, in many instances, to what is called a return sheller set aside

for the specific purpose of shelling rough rice returned from the paddy machines. The brown rice is conveyed to rice milling machines which remove the bran to produce milled rice.

Milling Machines

Rice mills are of basically two types: the abrasive type and the friction type. In the abrasive type, the bran is removed by contact against a moving rough surface as shown in Fig. 10-5A. The friction type functions by rubbing one kernel against another while the rice is subjected to a slight pressure, as illustrated in Fig. 10-5B.

Abrasive types

An example of the abrasive-type machine is a vertical cone mill shown in cross-sectional side view in Fig. 10-6. The feed of brown rice through hopper (1) is regulated by raising or lowering sleeve (2). The rice falls on the top of iron cone (4) and then on the abrasive surface of the cone (5). The rice passes between the abrasive cone and screen (6) (see exploded view on the left). The abraded bran passes through the screen where it is conveyed by the rotating blades (22) to the bran outlet (23). After passing through the polishing section, the milled rice is conveyed by moving blades (19) to the milled rice discharge (20). Provision is made for elevating or lowering the cone, altering the distance between the abrasive cone and screen, and thereby regulating the degree of bran removal. In addition, at periodic intervals around the screen are adjustable rubber brakes (shown in top view at the bottom of Fig. 10-6) which project into the space between

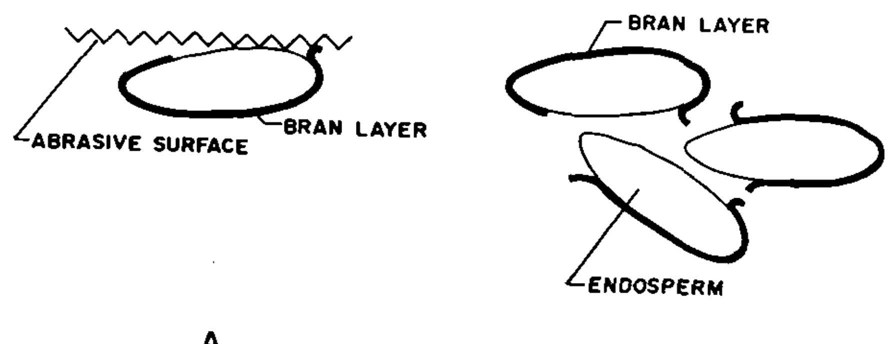

Figure 10-5. Milling principle of (A) abrasive- and (B) friction-type rice mills.

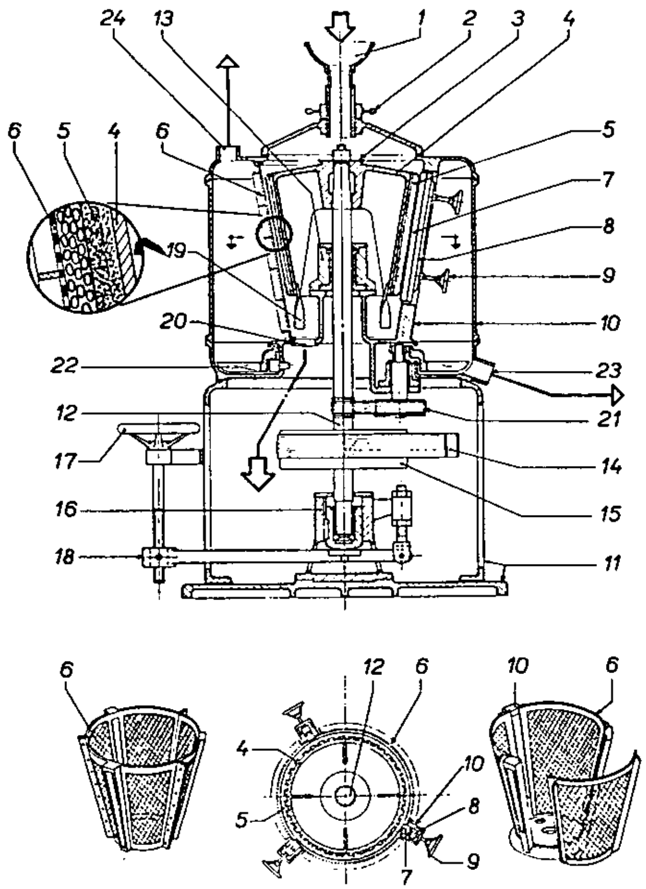

Figure 10-6. Abrasive cone mill. (1) Feed hopper. (2) Feed control handwheel. (3) Rotating cone clamping level. (4) Iron cone. (5) Cone abrasive surface. (6) Screen case (independent segment type) (bottom right). (7) Rubber brakes. (8) Rubber brake frame. (9) Rubber brake regulation handwheel. (10) Rotating cone housing. (11) Frame. (12) Cone shaft. (13) Upper bearing (central bearing-type cone). (14) Drive belt. (15) Drive pulley. (16) Lower bearing. (17) Screen and cone clearance adjustment handwheel. (18) Shaft supporting arm. (19) Milled rice conveyor. (20) Milled rice outlet. (21) Bran conveyor drive pulley. (22) Bran conveyor flight. (23) Bran outlet. (24) Air suction outlet. Courtesy of Food and Agriculture Organization of the United Nations (Borasio and Garibaldi 1957).

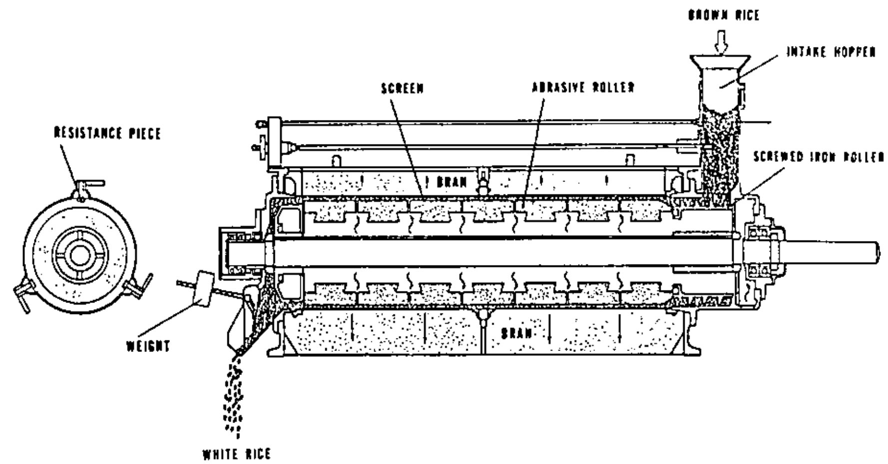

Figure 10-7. Horizontal abrasive-type mill. Courtesy of Satake Engineering Co.

cone and screen. The brakes retard the motion of the rice against the abrasive cone and thus help to regulate the degree of bran removal. The sides of the machine are provided with doors for periodic inspections of the screens and adjustment of the brakes by means of handwheels (9). Air is pulled through exit (24) to remove the warm moist air generated by the heating of the rice in the mill. Heat and moisture cause the bran to cake and thus to clog the holes in the screen.

In a horizontal abrasive mill (Fig. 10-7), brown rice is conveyed under a slight pressure into the space between a cylindrical abrasive surface and screen. No provision is made for altering the distance between abrasive surface and screen. Suitable brakes (resistance pieces) are provided. After passing through the mill, the rice emerges against an outlet plate which provides an adjustable back pressure by means of the weight to retain the rice in the mill. The pressure and retention time in the mill control the degree of milling of the rice.

Generally, rice is not milled in one pass through an abrasive mill but rather by passing the rice through two, three, or four mills in series. With several mills in series the pressure may be decreased and clearances in each mill increased with less breakage of rice. With increased clearances, mills in series have a larger throughput than a single mill producing the same degree of milling.

Friction type

A friction-type mill is illustrated in Fig. 10-8. Brown rice enters the mill through an adjustable feed gate. A short screw conveyer propels the rice under slight pressure into the milling chamber. A rotor (roller) with

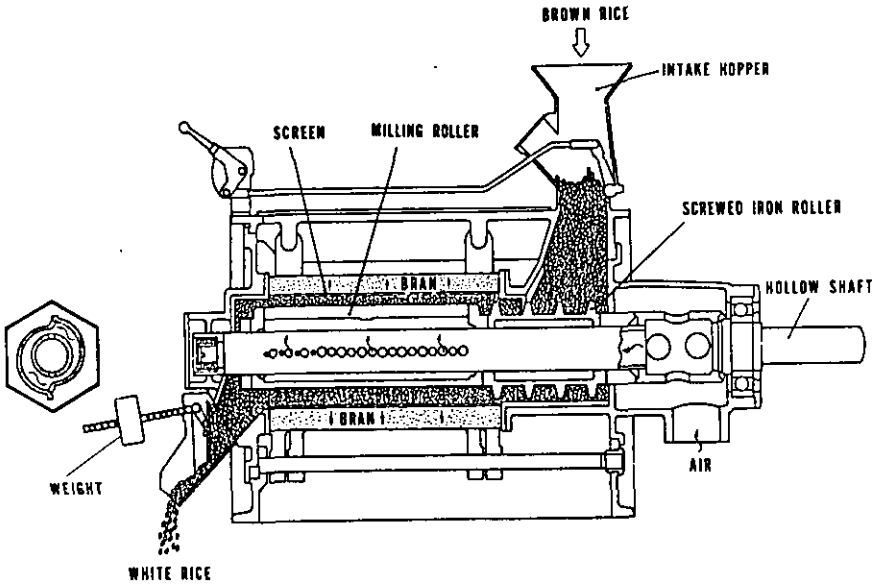

Figure 10-8. Friction-type rice mill. Courtesy of Satake Engineering Co.

projecting ridges imparts motion to the rice within a hexagonal slotted screen, as shown in the cross section perpendicular to the shaft (on the left of Fig. 10-8). The rotor in this case rotates clockwise. The rice emerges from the mill against a plate which is adjustable by weights to provide back pressure. The amount of back pressure affects the retention time in the mill and, in conjunction with the pressure applied by the screw conveyer, regulates the degree of bran removal. The rotor is hollow and is mounted on a hollow shaft so that air can be passed through the milling chamber. The air serves several functions: (1) it prevents the parts of the mill from heating up; (2) it cools the rice during passage through the mill; and (3) most importantly, it assists in separating the bran from the milled rice by blowing the bran through the slotted screen. This machine is capable of producing well-milled rice in one pass and is frequently used in this manner. However, two machines in series reduce breakage because pressures in the two machines can be decreased. A recent development in friction-type mills was reported in a patent (Meinardus 1985) that claims reduced breakage and greater milling efficiency.

Since rice bran is relatively soft compared to the hard endosperm, the frictional type machine has an advantage in that there is a sort of natural stopping point in producing well-milled rice. Removal of peripheral endosperm layers for various purposes, as discussed in the section on degree of milling, must be accomplished with abrasive-type machines.

The bran of parboiled rice is very sticky and must be removed in small increments using a series of abrasive-type mills. However, a frictional-type mill is frequently used in the last pass of milling parboiled rice to impart a smooth glossy surface to the rice. Frictional-type mills may also be used following abrasive milling of raw rice for the same purpose.

Polishing

As a final step, the milled rice is aspirated to remove loose bran. In addition, the milled rice may be passed through a machine called a brush or polisher to remove particles of loose bran. One type of polisher resembles the vertical cone mill except that leather strips replace the abrasive surface. By rolling the rice between the leather strips and the screen under very mild pressure, remaining loose bran is removed, and the rice is given a more polished surface. Passing the milled rice through trumbles, which causes the mass of grains to slide over one another, also helps to impart a smooth surface to the rice.

Sizing

The milled rice is sized by length to separate the whole kernels (head rice) from the "brokens." Based upon length, the brokens in the United States are separated into second heads, screenings, and brewers rice. U.S. standards for these classes are discussed further in Volume II, Chapter 5. A preliminary separation of whole grain from brokens may be made by use of screens. However, final separation is made by means of indented cylinders or indented disks shown in Figs. 10-9 and 10-10, respectively. Milled rice is introduced into the indented cylinder through hopper (1) to form a bed of rice along the bottom of the cylinder as shown in the bottom illustration of Fig. 10-9. The inside surface of the cylinder consists of small indented pockets whose size determines the separation made. As the cylinder turns clockwise, the indents become filled with both the shorter kernels to be separated and the longer kernels. As the side of the cylinder approaches a vertical position, the longer kernels fall out because the weight of the kernel extending past the lip of the indent is heavier than the portion within the indent. The shorter kernels fit within the indent, are carried further up the side of the cylinder, and fall into the collecting tray when the indent becomes inverted and unable to hold the shorter kernel. The position of the tray (6) is adjustable by handwheel (10). A screw conveyer (7) inside the tray discharges the shorter kernels through outlet (13). A grain spreader (12) helps to insure contact of all the grains with the indented surface. The longer kernels are discharged through outlet (14).

An indented disk separator consists of a number of indented disks rotating (counterclockwise in Fig. 10-10) through a bed of rice in the

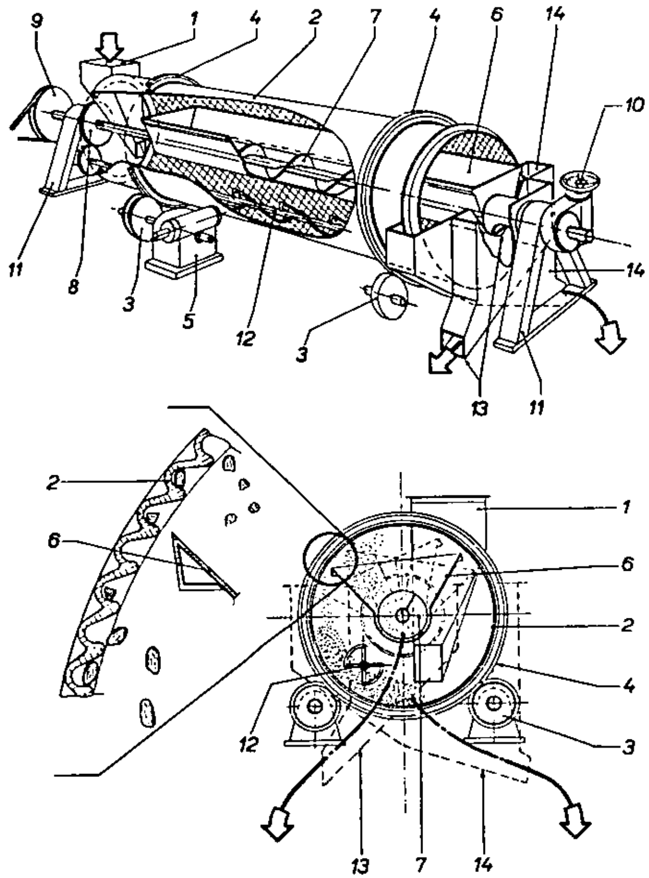

Figure 10-9. Indented cylinder separator. (1) Feed hopper. (2) Indented cylinder. (3) Cylinder supporting roll. (4) Outer cylinder ring. (5) Speed reduction unit. (6) Collecting tray. (7) Screw conveyor. (8) Screw conveyor and spreader driging gears. (9) Screw conveyor and spreader drive pulley. (10) Tray position adjustment handwheel. (11) Machine frame. (12) Grain spreader. (13) Liftings outlet. (14) Grain outlet. Courtesy of Food and Agriculture Organization of the United Nations (Borasio and Garibaldi 1957).

bottom of a U-shaped trough. Depending on the size of the indent pockets the short kernels are picked up as the disk turns through the bed of rice. The short kernels remain in the indents until the turning of the disk results in an inverted (upside down) position of the indent. At this point the grain falls out into the collecting trough (4). The longer kernels are conveyed by conveying flights (3) to grain outlet (9).

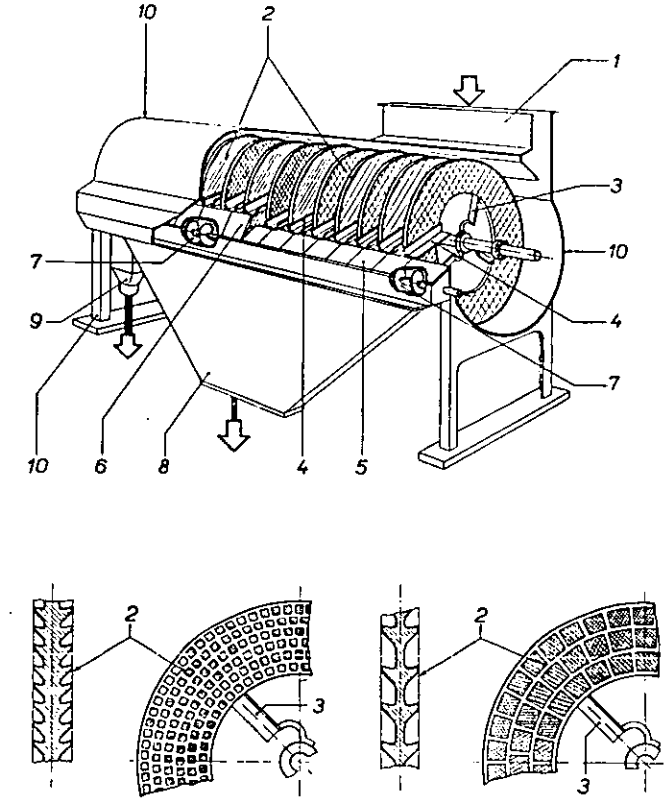

Figure 10-10. Indented disk separator. (1) Feed hopper. (2) Undercut pocket disks. (3) Grain conveying flights. (4) Liftings collecting trough. (5) Liftings trap door (closed). (6) Liftings trap door (open). (7) Liftings return screw conveyor. (8) Liftings discharge hopper. (9) Grain outlet. (10) Machine housing and frame. Courtesy of Food and Agriculture Organization of the United Nations (Borasio and Garibaldi 1957).

After separation, the whole grain and the various classes of brokens are weighed on automatic dump scales and then conveyed to separate bins. Bins are arranged along a conveyer belt so that rice from one or more bins can be combined and mixed to meet a buyer's specifications. The final step is to package the milled rice.

Photoelectric Sorting

In the case of parboiled rice, the percentage of breakage with modern processing is very small. However, parboiling enhances the discoloration of grains that have been damaged (discolored) by insects and/or microflora in the field. Thus, to produce a high quality parboiled rice, the discolored grain must be removed by photoelectric color sorting machines.

Bran Stabilization

When bran layers are removed from the endosperm during milling, the individual cells are disrupted, and the rice bran lipids come into contact with a highly reactive lipase enzyme. The resulting lipid hydrolysis reactions result in a very rapid increase in the free fatty acid content of the bran, making it unsuitable for the economical extraction of edible rice oil. A recent development (Sayre et al. 1982) has been the stabilization of rice bran by extrusion cooking. This stabilization takes place within minutes after milling, thereby minimizing the development of rancidity. After packaging the extruded bran product can be stored for several months. The stabilized bran is an excellent source of fiber for human consumption. Recent studies have shown that its cholesterol-lowering effect is equivalent to oat bran (Gerhardt and Gallo 1989; Kahlon et al. 1989). Also, the oil can be easily extracted from the bran with hexane, with excellent percolation rates, and refined to produce an excellent quality food-grade vegetable oil. A number of rice mills have recently acquired extruders and are evaluating their operation. Rice bran extruders seem likely to become standard equipment in rice mills.

Automation

As new rice mills are built and older mills modernized, more automation and computer control will be applied. Not much has been published in this area. Van Ruiten (1984) reviewed recent developments in equipment automation for the rice-milling industry. He discusses automation of individual pieces of rice-processing equipment as well as entire rice mills. Much of this information was obtained directly from equipment manufacturers.

Small Capacity Mills

In developing countries, small-capacity mills operated by local entrepreneurs may omit several steps of the milling process discussed above. Of particular note is the Engelberg huller mill. This is a friction-type mill which simultaneously removes both hulls and bran from rough rice. This machine has the disadvantages of producing high percentages of broken rice and discharging a byproduct mixture of bran and hulls. The bran is thus not as useful as a feed supplement or as a source of vegetable oil. These mills frequently only act as service mills to the farmer for home consumption. The mill has the advantages of minimizing the necessary investment in storage facilities and machinery and, being in proximity to producing areas, reducing the cost of transportation of the bulky rough rice. Another small mill uses a rubber roll sheller, an aspirator to remove loose hulls, and a friction-type machine to mill the approximately 95% brown–5% rough rice mixture from the sheller. In making well-milled rice, the rough rice in the mixture is shelled during the bran removal process and does not appear in the final product.

Coated Rice

Some rice consumers prefer a very glossy or shiny rice called coated or glazed rice. This rice is produced by adding calcium carbonate and corn syrup or a glucose solution to well-milled rice in a trumble. Rotation of the trumble evenly distributes the coating mixture over the grain. This technique is also used to fortify rice with vitamins and minerals. In the past, talcum powder was used in coating formulations for rice. However, this practice is now prohibited by the U.S. Food and Drug Administration (FDA).

RICE BREAKAGE DURING MILLING

The factors contributing to rice breakage during milling may be classified into two general categories: (1) those related to the properties of the rice grain itself, and (2) those related to the conditions of milling. The properties of the grain itself at the time of milling are determined by both the inherent varietal properties of the rice kernel and by the conditions to which the rice is subjected during growing, harvesting, drying, storage, transportation, and other handling (Kunze 1985). The conditions of milling affecting breakage are the rice temperature and moisture content during milling, the temperature and humidity of the milling environment, the degree of milling, and the operating conditions and mechanical settings of the milling machinery.

Factors Before Milling

Harvesting

To obtain high quality as well as high yield, rice must be harvested at the proper stage of maturity. If the crop is harvested too early (while immature), breakage during milling is excessive due to the large quantity of thin, light, and chalky kernels which are very fragile. If it is harvested too late, breakage during milling is excessive due to a phenomenon known as "sun checking" which is the development of cracks in the individual kernels. Smith et al. (1938) reported that delayed harvesting, which led to increased breakage of individual grains, was accompanied by decreased moisture content of the paddy rice.

Rice varieties differ in the range of harvest-time moisture content, or harvest moisture, at which they yield the best quality milled rice. Davis (1944) found that the optimal range for Caloro was 20 to 24%. Kester (1959), Kester and Pence (1962), and Kester et al. (1963) reported the optimal range for Calrose was 22 to 27%. Working with various short- and medium-grain varieties they found that milling head yields decreased between 0.9 and 1.7 percentage points for each one percentage point decrease in harvest moisture content within the harvest moisture range of 26 to 14%. When they hand harvested rice over a period of time while the field moisture content was decreasing from 47 to 15%, the milling head yields were best between field moisture contents of 32 and 25%. McNeal (1950), working with medium-grain (Zenith) and long-grain (Rexark, Nira, and Prelude) varieties, reported maximum milling head yields were obtained when the harvest moisture content was between 16 and 24%. Morse et al. (1967) reported maximum milling head yield for Caloro at between 26 and 30% harvest moisture. However, he also reported that total milled rice yield per acre continued to increase as the harvest moisture decreased to 12%. Below 26% harvest moisture, the increase in total yield was not very rapid. Johnston and Miller (1973) concluded that the optimal harvest moisture, considering both milling head yield and total milled rice yield per acre, is between 18 and 24%. New information continues to be released on the relationship between harvest moisture and milling yields for commercial and experimental rice lines (Miller et al. 1988; Dilday 1987).

Another harvesting factor that affects milling head yield is the mechanical action of the combine on the rice kernels. Matthews and Spadaro (1975) measured the effects of combining on rice breakage and head yield. In each of five fields, one rice sample was collected from a combine and another was collected by hand harvesting. X-ray photographs were used to determine the percentage of cracked and broken rough rice kernels. The combine-harvested samples averaged over five percentage points more cracked and broken rough rice kernels than the hand-harvested samples. This difference in breakage carried through the subsequent milling operations with the combine-harvested samples averaging 11.2% breakage while the hand-harvested samples averaged only 6% breakage. Dilday (1987) reported on both the influence of cylinder speed and the moisture content of the grain at harvest on the milling yields of rice. The current practice is to allow a small percentage of the kernels to crack during combining in order to obtain a maximum total yield per acre.

Drying

The optimal moisture content for harvesting rice is too high for safe storage; thus, the rough rice must be dried. The drying conditions to which the rice is subjected have a pronounced effect on breakage during milling. As the rice kernel dries, the outer portion shrinks, setting up stresses within the kernel. The magnitude of these stresses depends on the moisture and temperature gradients within the rice kernel, while the tensile strength of the rice kernel depends on its moisture content and temperature. If the rice is dried too rapidly, the internal stresses will exceed the tensile strength resulting in checking or cracking of the rice kernel (Henderson 1954, 1957; Kunze 1964; Kunze and Hall 1965; Choudhary 1970). These checked kernels are more susceptible to breaking during milling, resulting in reduced head yield (Rhind 1962).

The two rice-drying methods commonly used are (1) bin drying with unheated or slightly heated air (on-farm drying), and (2) multipass drying in continuous-flow heated air driers (commercial drying). A considerable amount of research has been done with these methods to determine economically feasible drying conditions that will minimize breakage during subsequent milling operations. Wasserman et al. (1958a) reported on drying procedures that increased drier capacity and simultaneously improved milled head yield for western U.S. rice varieties. Pominski et al. (1961) and Spadaro (1961) extended this work to varieties grown in the southern United States. McNeal (1961) investigated the effects of drying techniques and temperatures on milling head yields for four rice varieties: Arkrose, Bluebonnet, Nato, and Zenith. Sorenson and Crane (1960) reported on the practicality of drying rice in storage bins and presented equipment requirements and operating conditions to prevent loss in grade and milling yields. Calderwood et al. (1975) summarizes the methods and adjustments for increasing capacity of continuous-flow heated-air dryers without loss of milling quality.

Wasserman (1960) reported that tempering rice after drying without cooling (40.5°C) gave higher head yields than when the rice was cooled immediately after drying (23.8°C), and then tempered. Nguyen and Kunze (1984) reported on grain fissures related to post-drying treatments in rough rice.

Stipe et al. (1976) reported on a radically different method of drying rough rice which actually increases the milling head yields. Before drying, the naturally moist rough rice is exposed to live steam for a short time interval. The effect is to parboil lightly the undried rice. The steam-treated rough rice is then dried in a single pass with high-temperature air (80°C) to a moisture level of less than 13%. The key step in the process, the step that prevents breakage during milling, is to temper the rice immediately after drying for 1 h at 70°C in a sealed vessel. Wadsworth (1984) and Wadsworth et al. (1989) reported on the effects of microwave drying on milling yields. Green rice and parboiled rice could be microwave dried in a single pass without adversely affecting head yields.

Storage and handling

The conditions to which rice is subjected during storage and transportation also have an influence on the milling head yield. Several investigators have studied the effects of storage time after drying on milling quality with varied results. Wasserman et al. (1958a) reported that rice grown in the western United States could be milled immediately after drying without any loss in milling yields. Five lots of rice were each milled after drying and after 3, 6, and 9 weeks of storage. Milling yields did not change during these periods. Pominski et al. (1965), studying long- and medium-grain rice grown in the southern United States, also concluded that rice can be milled immediately after drying with no loss in head yield. He found that milling yields did not significantly change over a 4-week storage period. In addition, he reported some indication that higher head yields could be obtained with medium-grain rice by milling immediately following drying. The data of Wasserman (1961) on short-grain rice also shows higher head yields immediately after drying. Sorenson (1973) reported substantial increases in milling head yields (four to six percentage points) for rice stored over a 10-month period. This is in agreement with the work of Choudhary (1970), who found that the tensile strength of rice increased during storage. He concluded that during storage in a constant environment, the residual stresses induced by moisture gradients during drying may be gradually relieved, resulting in a stress-free kernel that has a higher tensile strength and therefore less likelihood of breaking during milling.

McNeal (1960) studied the milling of rice that was harvested and stored without drying for various periods of time at various moisture levels. He reported that the undried rice declined in grade before declining in milling yields. Wadsworth and Matthews (1985) reported that head yields in rice

that was held 24 h between harvesting and drying were slightly higher than those for rice dried immediately after harvesting. Calderwood and Schroeder (1975) investigated the use of chemical preservatives for maintaining undried rough rice in storage. They found that propionic acid, at levels sufficient to prevent moist rough rice from deteriorating, did not affect milling yields.

The environmental conditions to which the rice is exposed during storage and transportation are very important factors affecting milling yield. A significant amount of rice breakage during milling is due to rice kernels that have been weakened by stress cracks resulting from moisture adsorption or desorption. Kunze (1964) observed the development of fissures when rice kernels, equilibrated at storage moisture, were exposed to higher relative humidities. Kunze and Hall (1965, 1967) investigated the moisture adsorption characteristics of brown rice and relative humidity changes that cause brown rice to crack. They found that approximately 50% of the rice kernels, initially at storage moisture content, fissured within a 0.8 to 1.6-h period when exposed to 100% relative humidity at 33.3°C. The exposure time required for fissuring depended on the rice variety. Stermer (1968b) developed a relationship between stress crack damage and the magnitude of the change in equilibrium moisture content. Kunze and Choudhary (1971) found that the tensile strength of the rice kernels gradually decreased as the time of exposure to moisture adsorbing conditions increased even before physical fissures appeared. Therefore, even the kernels that have not developed cracks are more susceptible to breakage after exposure to adverse environmental conditions.

Since most rice is stored and transferred in bulk or in 45.4-kg burlap bags, minimizing its exposure to environments where moisture transfer may occur is important. Storage bin design and size are important for controlling the environment and preventing moisture migration. Bin height must be limited to prevent excessive breakage due to the weight of the stored rice. Transfer by belt, screw conveyors and bucket elevators can also lead to added kernel breakage by mechanical action. Louvier and Calderwood (1972) studied the breakage of rice due to falling impact such as would occur in the bulk loading of a ship. They reported that (1) the amount of breakage increased with dropping height up to 18.3 m; (2) long-grain rice was more susceptible to impact breakage than medium-grain rice; (3) breakage increased as the moisture content of the rice was reduced; and (4) the relative humidity and temperature of the air through which the rice fell had little effect on impact breakage.

Kernel damage due to improper storage and/or insect infestation can lead to increased breakage. Schroeder (1967) reported reduced head and total milling yields resulting from invasion by storage fungi in experimental rice storage studies. Calderwood et al. (1984) reported that the milling yields of rice in long-term storage at 12% moisture content could be maintained by aeration.

Parboiling

It is common knowledge that parboiling will greatly improve the milling quality of rice such that head yields will approach total yields (i.e., zero breakage). Bhattacharya and Subba Rao (1966) and Bhattacharya (1969) have conducted comprehensive quantitative studies on the effects of parboiling on the breakage of rice. They reported that kernel defects such as cracks, chalkiness, and incomplete grain filling are completely healed during the parboiling process. When properly dried, the rice kernels are very resistant to mechanical breakage. Thus, the milling quality of parboiled rough rice is determined by drying conditions following parboiling and is independent of the previous history or condition of the rice. Consequently, for rough rice that is to be parboiled, the optimal harvesting, drying, and storage conditions should be selected on some basis other than that of preserving the milling quality. For the same reasons, parboiling is an excellent means for salvaging rice whose milling quality has been inadvertently damaged by improper handling or processing.

Milling Factors

During the shelling and milling (bran removal) operations, the rice kernels are subjected to mechanical forces to remove the husk and bran and produce white milled rice. Milling will cause breakage of some kernels even in rice lots which have been harvested, dried, and stored with extreme care. For lots that have been subjected to poor treatment, milling may break every grain. The ideal milling operation is one in which the mill environment, rice properties, and machine settings are controlled to minimize breakage (maximize head yield) while producing rice with the desired degree of milling.

Defective kernels

Several investigators have studied the relationship between the amount of checking or cracks in the rice kernels and the amount of breakage occurring in the milling operations. Reports on the degree of correlation between defective kernels and breakage vary. Autrey et al. (1955) did not find any correlation for medium- or long-grain rice between the percentage broken during shelling and that broken during milling. Nor was any correlation seen between the defective kernels as received and breakage during milling. Hogan et al. (1954), using X-ray technique (radiographs) to evaluate the percentage of cracked rough rice, also did not find a correlation between the percentage of cracked before milling and broken milled rice. He concluded that either the grain had cracks which could not be detected radiographically or milling head yields were affected by other factors. McDonald (1967), who studied factors influencing rice checking in Australia and the effects of checking on milling quality, concluded that milling quality (head yield) is not related to the percentage of cracked rough rice kernels, and the only way of assessing it is by test milling.

In contrast to the above findings, Ten Have (1958) found for five varieties of long-grain rice that the percentage of cracked rough rice kernels, determined by hand shelling and visual inspection of the brown rice, had a good correlation with breakage during milling. In rice lots with low percentages cracked and low breakage, the percentage of brokens generally exceeded the percentage cracked. In rice lots with 20% or more breakage during milling, the percentage of brokens was less than the percentage of cracked rough rice kernels. Henderson (1954), who determined cracks in rough rice by X-ray examination, reported that many of the internally or incipiently cracked rough rice kernels of short-grain Caloro did not break when milled. The amount that may be cracked but unbroken after milling may range from 0 to 86%. He examined a sample of short-grain rice obtained from a local retail grocer and found 65% of the whole kernels had cracks. Stermer (1968b), who determined stress cracks with transmitted polarized light, reported that in limited mechanical breakage tests on long-grain Belle Patna and medium grain Nato varieties, rice kernels showing stress-crack damage were easily shattered. Bhattacharya (1969), using transmitted light to determine cracked kernels visually, reported that breakage during milling was related quantitatively to the amount of cracked and immature kernels. He concluded that it is principally the defective grains that ultimately fail in rice milling.

Matthews et al. (1970) made a comprehensive investigation of the relationships between breakage during milling and defective rough rice kernels as determined by X-ray examination. He reported that grain type (long, medium, or short) is extremely important in the relationship between defective kernels and milling breakage. For long-grain rice he demonstrated a proportionality between the percentage of cracked rough rice kernels and the percentage of broken brown and milled rice. Only one-third of the breakage after milling could be attributed to rough rice kernels that had an observable crack in a position to give rise to a broken milled rice kernel. The low proportion of cracked rough rice to broken milled rice could be due to the inability of the X-ray technique to show all cracks. An alternative explanation is that the percentage of cracks is indicative of a residual stressed condition in the apparently sound kernels. They recommended additional research to determine the relationship between cracks observable by X-ray examination and cracks observable by such visual methods as described by Stermer (1968b) and to determine the nature of the fragility of long-grain kernels which break but do not have an observable crack. For medium-grain rice, Matthews et al. (1970) reported that the percentage of cracked rough rice kernels was approximately equal to the percentage of those broken after milling. About one-half of the cracked kernels broke during shelling. The greater resistance to breaking of cracked medium-grain kernels is probably related to the thicker, more rounded kernel as compared to long-grain rice. Henderson (1954) has shown that cracked short-grain rice kernels can be very resistant to breakage with a high percentage of them surviving milling intact. Sorenson (1973) confirmed the importance of grain type in the relationship between cracked rough rice and broken milled rice. He reported that long-grain stress-cracked rice kernels are very fragile and break easily during milling. The medium-grain stress-cracked kernel very often withstands milling without breaking. He concludes that breakage is only partially related to the quantity of cracked kernels in the rough rice.

Kernel size

Several investigators have reported that long-grain rice is more susceptible to breakage during milling than medium-grain rice, which in turn is more susceptible than short-grain rice. Matthews and Spadaro (1976) investigated the relationship between kernel thickness and breakage for long-grain rice. Six lots of three varieties of long-grain rough rice were each separated by thickness into four fractions. X-ray photographs were used to determine the percentage of cracked kernels in each rough rice thickness fraction. They demonstrated that, for a given lot of rice, the thinner kernels are more susceptible to breakage during milling. They also demonstrated relationships between cracked rough rice and broken milled rice that were dependent upon the thickness of the kernels.

Wadsworth et al. (1982) and Wadsworth and Hayes (1989) reported on the variation of milling performance and quality characteristics of long-, medium- and short-grain rice related to the thickness of the rough rice kernels. They found significant differences in shelling efficiency, brown rice yield, total and head yields, processing losses, and milled rice quality associated with kernel thickness. Their results identified several advantages that could be realized by rice processors if they separated the paddy rice by kernel thickness before milling. These include the reduction of processing losses, improved efficiency, improved milled rice quality, and production of a new higher protein rice raw material suitable for development of new food products (Wadsworth and Hayes 1986). The processor would have additional flexibility to blend rice to obtain specified grades or meet buyers' specifications based on factors other than percentage of broken kernels. The rice-cleaning equipment currently in place at most modern rice mills should be suitable for separating paddy rice into fractions of differing thickness.

Rice moisture content

The effect of rice moisture content on milling head yield has been the subject of several investigations. Pominski et al. (1961) reported that moisture content had a very significant effect on milling yields of Bluebonnet 50 long-grain rice. Over the range of 10 to 14% moisture, head yields and total yields increased by approximately 3 and 0.7 percentage point, respectively, for each one percentage point decrease in rice moisture. Wratten (1960) also reported that lower moisture content increased the milling yields of Bluebonnet 50. Wasserman (1960, 1961) demonstrated that milling yields of Caloro short-grain rice varied inversely with moisture content. Over the range of 10 to 14% moisture, the head and total yields increased by 1.8 and 1.2 percentage points, respectively, for each one percentage point decrease in moisture. He obtained similar results with California Pearl short-grain rice. He also showed that the total yield of the milled rice could be further increased by remoistening it to normal moisture content. The remoistening was done by exposing the milled rice to humidified air under carefully controlled conditions such that there was little increase in breaking or cracking. Bhatia (1969), using Saturn medium-grain rice, found that with each one percentage point decrease in moisture from 12 to 10%, the breakage decreased by 1.6 percentage points.

Webb and Calderwood (1977) investigated the relationship of moisture content to the degree of milling in rice. They reported that rice with low moisture levels (6–10%) was markedly more resistant to milling at a specified mill setting than samples at higher moisture levels. The low moisture samples required considerably more milling pressure to obtain an equivalent degree of milling. As expected, head yield of the low moisture samples at a conventional mill setting was greater than that of the higher moisture samples, but the difference in head yield between low moisture and higher moisture samples was greatly reduced or eliminated when mill settings were adjusted to obtain an equivalent degree of milling.

Stipe et al. (1972) investigated the effects on milling yields of shelling rough rice at higher than normal moisture content, drying the brown rice to normal milling moisture content, and milling. They found that, with Saturn medium-grain rice, a considerable decrease occurred in both total and head yields when the moisture content was above 18% during shelling. Shelling tests with two long-grain varieties, Dawn and Starbonnet, showed significant reductions in head yields when shelled at moisture contents of 16 to 18% as compared with the 12 to 14% levels. Kassem and Kunze

(1984) reported on flash drying techniques that enabled them to shell high-moisture rough rice efficiently without affecting head yields.

Temperature

Autrey et al. (1955) investigated the effect of temperature on breakage during milling. He reported that, while the actual temperature of the rice or the mill room was not related to breakage, the difference between the temperature of the rice entering the mill and the temperature of the mill room itself could be correlated with head yield. When the temperature of Zenith medium-grain rice was 5.5°C higher than that of the mill room, head yields decreased by an average of 1.6 percentage points. When the rice temperature was 5.5°C below the room temperature, the decrease in head yield averaged 0.9 percentage points. Rexark variety rice was less sensitive to temperature than was the Zenith. Rhind and Tin (1933) reported that for each degree centigrade higher rice temperature at time of milling, there was a decrease in whole kernel yield of between 0.5 and 1.0 percentage points. Henderson (1954) also observed that higher temperatures enhanced breakage. Sorenson (1973) milled rice with liquid nitrogen being passed through the mill rotor and through the rice while it was being milled. He found that higher head yields were realized with the liquid nitrogen cooling; however, because of mechanical problems encountered during milling, he believes that the study is inconclusive and the use of liquid nitrogen is impractical for cooling rice during milling. Bhatia (1969) varied the temperature of rice before milling from 21.1 to 32.2°C with various rice moisture contents. His data showed that breakage during milling actually decreased slightly as the initial rice temperature increased.

Later work has indicated that the effects correlated with temperature changes may actually be related to moisture gain or loss in the rice kernel which accompanies the temperature changes. Kunze and Hall (1967) reported that subjecting rice kernels to a large temperature change—up to 34.4°C degrees—while controlling the relative humidity such that no moisture changes occurred, did not produce any cracks in the kernels. They concluded that the effect of temperature gradient on breakage is small. Matthews et al. (1971) subjected long-grain rough rice to a combination of time–temperature treatments in hermetically sealed containers to minimize moisture transfer. Duration of heat treatments varied from 2 to 19 h and temperature from 60 to 120°C. Results indicated that heat by itself was not detrimental.

Relative humidity

In the rice industry, moisture changes in the rice kernel are recognized to be closely related to stress cracking. The relative humidity of the environment in which the rice is milled can be an important factor in the moisture changes, and several investigators have studied the effect of this aspect of milling on head yield. Autrey et al. (1955) investigated this in a pilot plant with closely controlled humidity, using three varieties of raw rough rice and one sample of parboiled rice. The mill room temperature was maintained at 29.4 ± 1.1°C. The optimal relative humidity (RH) for processing the rice was found to be approximately 70%. The rice used in these tests had a moisture content of around 13% and, thus, was in moisture equilibrium with 29.4°C air at about 70% RH. These conditions would minimize moisture transfer to or from the rice. When relative humidities above or below 70% were used, the resulting head yields decreased. The effect of humidity on head yield was different for different rice varieties. For Bluebonnet, the range in head yield was 3.2 percentage points over a range in humidity from 50 to 70%; for Zenith, 1.8 percentage points over the same humidity range. The relative humidity had little effect on the head yield of the parboiled sample. The results obtained in the pilot plant were verified in commercial mills where a pronounced decrease in head yields was found when milling was done on days with low relative humidities. In another series of pilot-plant experiments, Autrey regulated the humidity in various pieces of equipment at 70% while the mill room was at 30%. He concluded that near optimum head yields could be obtained by regulating the humidity just in the pieces of equipment where the rice is exposed to large volumes of air.

Aeration during bran removal

Several investigators have reported increased milling head yields due to blowing air through the rice while the bran is being removed. Bhatia (1969), who studied milling in a ventilated Engelberg huller, reported that breakage could be reduced by approximately 3 percentage points by providing 4.34 m^3/s ventilating air per m^3 of annular space in the huller. The aeration lowered the temperature of the rice during milling. He concluded that breakage is a function of the increase in temperature of the grain during the milling process. Bhatia also controlled the humidity of the ventilating air. The controlled-humidity air was in contact with the rice only for the short time the rice was in the mill. While Bhatia concluded that the effect of humidity on head yields was negligible, his data show that the trend is similar to that found by Autrey et al. (1955). With ventilating air at 50% RH, the average breakage during milling was 13.7%, with 70% RH, the breakage was 12.8%, and with 90% RH, the breakage was 14.3%. Wasserman et al. (1974) reported that aerating the rice during milling with a CeCoCo continuous abrasive-type mill decreased milling time by 6% but had little effect on head yield. Matthews and Spadaro (1974) reported that for the Satake Jet Pearler, the head yield increased as the ventilating airflow rate through the mill was increased. Childers et al. (1975) studied the effects of aerating during milling in a McGill Number 3 batch-type mill. In tests with long-grain rice, head yields increased from 2.0 to 4.5 percentage points with aeration. For medium-grain rice the increase in *head yield* was about 3 percentage points. Childers et al. also controlled the relative humidity but did not find any relationship between humidity and head yield. However, the rice was aerated for only 1 min at a relatively low airflow rate (0.0033 m^3/s), and they believe additional tests at higher flow rates are needed to determine the full effect of relative humidity on head yield with a batch-type mill.

Both Childers et al. (1975) and Bhatia (1969) concluded that, because the unaerated rice reached higher temperatures during milling, it was subjected to greater thermal stresses, which probably caused the rice kernels to be broken more easily. Another *possible explanation* for the decrease in breakage with aeration is that the lower breakage is the result of decreased moisture gradient stresses rather than thermal stresses. Matthews et al. (1971) and Kunze and Hall (1967) reported that subjecting rice to large temperature gradients but under conditions where no moisture transfer occurred did not result in the development of cracks due to thermal stresses. Mannapperuma (1974) analyzed the stresses inside a rice grain due to temperature and moisture gradients. An axisymmetric model with *an elliptical longitudinal* section was developed using finite difference methods to represent the rice kernel. He calculated that exposure to a 41.7°C temperature gradient results in a thermal tensile stress of 1.72×10^6 Pa (250 lb/in^2) at the center of the kernel—well below the rupture stresses in tension and compression. Several investigators have shown that moisture-gradient stresses alone can cause a rice kernel to crack. When the rice heats up during milling, the vapor pressure of the water in the rice increases, resulting in a higher rate of water transfer from the rice kernel to the surrounding air. Aerating the rice during milling reduces the rice temperature and removes heat which would otherwise be available to evaporate the rice moisture, thereby reducing the rate of moisture transfer and the stresses resulting from the moisture gradient. To clarify this point, additional precise experimental data need to be collected on the changes occurring during milling in rice moisture content and temperature as well as changes in the temperature and humidity of the air surrounding and flowing through the rice.

Milling time

One area of milling which has considerable conflicting information in the literature is the effect of the duration of milling on breakage. Autrey et al. (1955), working with both medium- and long-grain rice, reported that only about one-fifth of the breakage occurs during the time period required to remove 75% of the bran. When the milling time is extended to remove the remaining 25% of the bran, about four-fifths of the breakage occurs. R[illegible] (1962) stated that, in his experience, the stress-cracked kernels are present in every sample, and these defective grains break as soon as *milling* starts. Thereafter, breakage proceeds steadily as the rice is subjected to more and more force as milling continues. He believes that badly cracked kernels are destined to break and do so with a minimum of milling. Smith and McCrea (1951) milled numerous large samples of many different varieties of rice for times ranging from 15 to 90 s. They reported that the highest percentage of breakage occurred during the first 15 s of milling in all of the tests, and from that time on, the breakage was small. Bhattacharya and Subba Rao (1966) reported that most of the breakage in a lot of rice occurred at the *earliest stage and increased little with* continued milling. Bhatia (1969) concluded that, on the average, 70 to 80% of the total breakage occurs during the first 5 s of mill operation, and from that time on, the breakage is comparatively small. Matthews et al. (1970), working with both long- and medium-grain rice, reported that almost all of the breakage occurred in the first 10 s of milling. About 70% of the bran was removed in the first 10 s. Bran removal continued, although at a decreasing rate for the entire milling period. The polishing period could be extended for about 150 s without increasing breakage *significantly over that taking place in the first* 10 s of milling. They concluded that the breakage is due to mechanical stresses and not to moisture or thermal stresses which develop continuously as milling proceeds. They hypothesized that the major reason that breakage is not completed in the first 1 s of milling is probably that not all of the kernels have been mechanically stressed by this time. For example, the rice kernels at the end of 5 s of milling consisted of about 40% well-milled grains and 60% which had hardly been milled at all, rather than consisting of a uniform collection of grains, each having about 40% of the bran removed (such as might be inferred from the 40% total bran removal achieved with 5-s milling time). Hogan (1969), investigating the effects of deep milling rice by abrasion to produce a high-protein rice flour, reported that kernel breakage progressively increased as overmilling proceeded. The breakage of the long-grain types was greater than that for medium- and short-grain varieties. Bajaj and Sidhu (1984) also reported gradually decreasing head yields in their study on extended milling of Indian rice.

Additives

Matthews et al. (1971a) stated that, in present commercial practice, the amount of long-grain rice broken at the end of the shelling process represents only 25 to 45% of the total broken rice after milling. Therefore, a chemical or physical treatment of the brown rice to facilitate bran removal could potentially reduce a major portion of the total breakage occurring in conventional milling.

Autrey et al. (1955) studied the effects of steaming brown rice before milling. While steaming, they found that droplets of water should not be allowed to come into contact with the rice and that the temperature of the rice should not be allowed to rise appreciably. When either of these conditions occurred, the result was a decrease in the head yield. Optimum results were obtained when the brown rice came out of the steam bath slightly damp and at a temperature near its entering temperature. With properly dried rice, steaming had no significant effect upon head yield; however, the mill capacity was increased. With rice that had low head yield due to improper drying or storage, the head yield was increased significantly by steaming. They conclude that steaming results in lesser adherence of the bran to the endosperm, thus requiring less mechanical force for bran removal. Obtaining higher head yields by exposing the brown rice to moisture before milling appears to be in direct conflict with the work of Kunze and Hall (1965) who showed that moisture adsorption caused brown rice to develop stress cracks. However, Choudhary (1970) reported that the initial short-term effect of moisture adsorption was an increase in the tensile strength of the rice kernel. He stated that this behavior was not anticipated, and additional research is required for an explanation of this phenomenon.

Autrey et al. (1955) also studied the effects of adding abrasives (calcium carbonate, fine bauxite, coarse bauxite, and Attaclay) to the rice during milling. The most efficient milling additive was calcium carbonate. However, like steaming of properly dried and stored rice, abrasive had no significant effect on head yield but did increase mill capacity. The head yield was increased by using abrasives on rice that had been improperly dried or stored. When both steam and calcium carbonate were used together, there was greater improvement in mill capacity than when either was used alone.

Matthews et al. (1971b) reported on the treatment of rough rice with ammonia and sulfur dioxide gases to loosen or soften the bran. Treatments ranged from 3 to 15 h in hermetically sealed containers. Milling yields were not improved over the untreated control. Ammonia-treated samples acquired a yellow color in the endosperm, and expelling the gas from the rice under vacuum was difficult. Sulfur dioxide bleached the endosperm, and the resulting milled kernels were an attractive white color, but ridding the rice of the residual gas odor was no easier.

Roberts and Wasserman (1977), Wasserman and Roberts (1972), and Wasserman et al. (1974) investigated wet milling with and without various additives including calcium carbonate, whole or ground rice hulls, and rough rice. The effects of most of the additives showed reductions in milling time and energy consumption and increases in total and head rice yield when compared to runs with no additives. The addition of water gave favorable results in every case. The addition of 5% rough rice was not as effective as whole or ground hulls. Because mill settings were changed for the tests using calcium carbonate, the effect could not be directly compared with those of other additives, but in combination with water the results improved markedly. In the case of water addition, breakage was reduced as holding time between the water addition and the milling operations was shortened. When abrasive solids were used, with or without water, the Engleberg mill settings had to be adjusted to remove less bran and polish per pass in order to prevent stalling of the equipment.

Morgan et al. (1966) reported on the chemical milling of rice. The bran is chemically loosened by strong warm lye and then physically removed by vigorous water washing. The product retains all the endosperm, including the aleurone layer, but loses most or all of the colored bran layers. Warm dilute acid restores the surface whiteness and the grain is dried in warm air.

Solvent extractive milling

Radically different in rice-milling technology is the solvent extractive milling (SEM) process (Wayne 1965a, b, 1966, 1968). The SEM process differs from conventional rice milling in the method of bran removal and in the processing of byproducts. With the SEM process, the bran layers are first softened, then wet milled in the presence of a rice oil-hexane miscella. In addition to milled rice, byproducts, crude rice oil, and defatted rice bran are obtained.

Lynn (1966) reported details of the SEM process, and Lynn and Lawler (1966) presented a detailed flow sheet for the 1.5 million bbl/yr plant at Abbeville, LA. This plant closed recently because it would have been prohibitively expensive to install the environmental controls necessary to meet new hexane emmission standards.

In the SEM process, the bran softening is accomplished by spraying warm rice oil onto the brown rice in closely controlled amounts (approximately 0.5%) and with uniform distribution. The treated brown rice is held for 2 to 4 h to allow the rice oil to permeate the bran membranes and soften them. After the holding period, the treated rice with the softened bran is conveyed to Satake Rice Pearling machines which have been sealed and provided with solvent ports to permit the flow of large volumes of temperature-controlled solution of rice oil in hexane (*miscella*) throughout the rice during milling. The miscella acts as a washing and rinsing medium to aid in flushing the bran from the rice endosperm as well as a conveying medium for continuously transporting the removed bran away from the rice. In addition, the miscella lends additional lubricity to the rice. These factors reduce the amount of pressure required during the bran removal operation which significantly reduces the amount of breakage.

Following the bran removal step, the rice is rinsed with additional hexane on vibratory screens. It is then drained of the excess solvent and conveyed to desolventizing equipment. Superheated hexane vapor is used to flash evaporate the bulk of the hexane remaining on the rice. Then the rice is treated with flowing inert gas which removes the last traces of solvent. At this point, the SEM process for the milled rice is completed, and the rice is sized, graded, and packaged with conventional mill equipment.

The slurry of bran, rice oil, and hexane (15–20% bran) is pumped from the milling equipment to vessels where it is allowed to settle and the extraction of the oil from the bran is completed. The remaining bran-processing steps are used to separate the solid bran from the liquid stream.

The SEM process has some advantages over conventional abrasion and frictonal pressure milling (Lynn and Anderson 1967). The rice is whiter and more attractive than conventionally milled rice and has a significantly lower fat content. The white color is believed to result from more complete removal of the surface fats and color bodies by exposure to solvents.

Consumer evaluation of the SEM rice in direct comparison with conventionally milled rice has shown no major dissimilarities between the two products. The color of the SEM rice is generally cited as a preference factor. Taste and smell are about the same as with regularly milled rice. The SEM product has less "stickiness." The cooked flavor, texture, and appearance have not been altered materially.

The lower fat content of SEM rice contributes to excellent storage stability. This is particularly important in packaging rice, since problems of fat "bleedthrough" frequently occur, resulting in the obliteration or smearing of the printed labels on transparent packaging materials. Consequently, fewer packaging plys are required for SEM rice.

Improved brewing performance because of reduced fat content is an indirect product advantage of SEM rice. Excessive fat level interferes with the fermentation process in brewing beer.

A significant difference in the SEM process and conventional milling is that two essentially new products are directly produced from SEM: defatted rice bran and crude rice oil. The defatted rice bran produced by SEM contains 17 to 21% protein and approximately 1.5% fat. The SEM crude rice oil produces a light colored edible oil when refined by conventional alkali methods followed by customary bleaching and deodorization.

Machinery settings

Other factors that affect breakage during milling are the mechanical settings. In commercial mills, the mill settings are adjusted by the operator based on his visual inspection of the milled rice, a technique that can be inconsistent. Ideally, the mill should be adjusted such that a given degree of milling (percentage of bran removal) is obtained while minimizing breakage and maximizing milling capacity. The adjustable settings vary with the type of mill being used.

Matthews and Spadaro (1974) investigated the factors contributing to breakage in a Satake Jet Pearler Model BA-3 which is a small model of the Satake BA-15 used in many rice mills. They reported on the effects of rotor speed, feed-gate opening, back pressure, and number of passes on breakage, degree of milling, energy consumption, and production rate. Higher rotor speeds resulted in less breakage. The wider feed-gate openings increased both production rate and breakage. Higher back pressures resulted in a greater degree of bran removal and breakage. Two passes were superior to one pass in effecting the same degree of bran removal with less breakage.

Wasserman et al. (1974) and Roberts and Wasserman (1977) investigated the effects of mill settings for a CeCoCo mill which removes bran by abrasion against an emery cone, and a small Engelberg mill which rubs grains against each other under pressure. They found that mill settings had little effect in the CeCoCo. Mill settings in the Engelberg were more critical. As the feed gate was adjusted from half open to fully open, milling time and energy use were reduced 23% and 21%, respectively, but head yield decreased about 1.5 percentage points. As the discharge gate was opened gradually over its operating range, milling time was shortened up to 60%, and energy requirements were reduced up to 55%. Yields of total rice changed very little, but head rice yields increased by about five percentage points. As the milling pressure was increased by moving the pressure bar closer to the rotor, milling time was reduced up to 59%, and energy consumption was reduced up to 34%. However, total yield was about one percentage point lower, and head yield decreased about six percentage points.

DEGREE OF MILLING

The term "degree of milling" refers to the percentage of bran removed on a rough rice basis. In USDA grading practice, the degree of milling is one of the factors that determines the grade assigned to the milled rice. For each grade there are maximum limits of objectionable factors such as weed seeds, damaged (discolored) kernels, chalky kernels, etc. The maximum allowable limits of these objectionable factors increase with decrease in degree of milling so that the less well-milled rices are of generally lower quality and bring a lower price in the market.

Effect on Nutritional Properties

Generally, a well-milled rice is preferred by the majority of rice consumers. Brown rice is preferred by a relatively small percentage of consumers even though it contains more protein, vitamins, minerals, and lipids than milled rice. Part of the reluctance of consumers to eat brown rice is its chewier texture and strong flavor. Brown rice also requires a cooking time of about 45 min compared to about 20 min for milled rice. Between the extremes of brown rice and well-milled rice is rice that has been lightly milled or undermilled, thus retaining part of the bran. In some developing countries, such as India (Desikachar 1967), the government has enforced the production and consumption of undermilled rice to make the maximum possible use of rice resources and improve the nutritional value of the rice. The Indian government has fixed as a maximum a 3 to 4% degree of milling for rice to be consumed in India. These figures may be compared to the 8 to 9% degree of milling of a well-milled rice. The 3 to 4% degree of milling allows for rapid water penetration and a cooking time comparable to well-milled rice. The main drawback of lightly or undermilled rice is its tendency to become rancid, particularly after storage of about two months. Since in developing countries the rice is generally consumed within this period, there are no practical difficulties encountered. Bajaj and Suhid (1984, 1989) and Bajaj et al. (1989) reported on the effects of milling time on quality characteristics and nutrient composition of several varieties of Indian rice. As milling time increased, the cooking quality of the rice, as measured by elongation ratio and water uptake, improved, but the nutritional quality, as measured by protein and mineral contents, decreased.

Measurement of Degree of Milling

In conventional rice milling and grading practice, the degree of milling is estimated subjectively by visual observation and comparison with standards. However, this subjective means of measurement is not considered completely satisfactory. A number of investigators have been concerned with the development of objective methods for evaluating degree of bran removal. These methods may generally be classified as chemical or physical in nature.

Chemical methods that have been investigated consist of differential dye staining procedures to enhance the visual differences between endosperm and bran, and chemical analysis for constituents that occur predominantly in the bran. Desikachar (1955a) and Borasio (1955) developed differential dye staining techniques. Although the detection of bran is enhanced, the assignment of a degree of milling still has an element of subjectivity. Differential dye staining has been developed into a quantitative procedure by Barber and Benedito de Barber (1976). Milled rice kernels are stained with a methylene blue and eosine solution in methyl alcohol. Areas covered with bran stain blue while the endosperm stains pink. The bran and total kernel areas of magnified plane images are measured by planimetry. Colored bran balance (CBB) values range from 100 for brown rice to 0 for complete milled rice. This method is of particular interest in that it permits evaluation of the homogeneity of milling. Measurements of the degree of milling through analysis of constituents that occur predominantly in the bran include assays for thiamin (Kik 1951a; Desikachar 1955b), phosphorus (Desikachar 1955b), surface lipid (Autrey et al. 1955; Hogan and Deobald 1961), surface lipid, ash, and protein (Watson et al. 1975).

Physical methods for determining the degree of milling have generally utilized the optical characteristics of the kernel. These methods depend upon the reflection of light from and the transmission of light through the milled rice at selected wavelengths. Kik (1951b) and Angladette (1957) were developers of optical devices for measuring the degree of milling. Stermer and co-workers (1962, 1968a) developed improved optical instruments. The main difficulty encountered in the use of optical devices is the presence of chalky kernels in the rice to be measured. The chalky kernels are not optically translucent and thus interfere with accurate measurements. This drawback can be remedied by removing the chalky kernels by photoelectric sorting machines before making the measurement of degree of milling.

A new physical method that shows promise is based on the total lipid content of the rice measured by nuclear magnetic resonance (Pomeranz et al. 1975). Near infrared reflectance spectroscopy is also being used to estimate degree of milling in rice (Hopkins and Kencaster 1980; Stermer et al. 1977; Kao 1986, 1988; Wadsworth et al. 1990).

Deep Milling

The removal of peripheral layers of well-milled rice (endosperm) is termed deep milling or overmilling. Because of the hardness of the rice endosperm, deep milling must be accomplished with abrasive-type mills. Research on deep milling (Hogan 1969) has shown that (1) there is a heterogeneous distribution of protein and other major noncarbohydrate nutritional constituents in the milled rice kernel; (2) below the bran coat and aleurone cells, which are removed during conventional milling, is a peripheral layer unusually high in protein, minerals, lipids, and vitamins; (3) the high protein and naturally enriched layer may be removed by presently available commercial machinery in the form of a finely divided rice flour, which may be considered an extension of the regular milling operation; and (4) the intact residual kernels, although reduced slightly in the nonstarch nutrients, are essentially an attractive white and well-milled rice suitable for regular table and food uses.

Normand et al. (1966) determined the amount of certain nutrients and the amino acids pattern in high protein rice flour produced by deep milling. They reported that the prepared material, which was removed in 12 fractions from successive layers of commercially milled rice, consisted of approximately 18% of the original kernel weight as finely divided flour with a 22 to 12% protein content. Fat, thiamin, riboflavin, niacin, phosphorus, and calcium similarly decreased progressively from outside layers toward the center of the kernel. Starch and amylose, by contrast, progressively increased toward the center of the rice kernel. The increase (approximately 19%) in amylose content of the rice starch from outer to inner layers reflects a significant difference in rice starch composition. The data indicated no essential differences in amino acids content of the rice protein except for a decrease in tryptophan toward the center of the kernel.

Sensory evaluation of the residual kernels remaining after different degrees of deep milling showed an increase in cooking quality preference with increasing degrees of milling up to a maximum, after which further milling gave a loss of quality (Hogan 1969). Cooked rice samples were evaluated for cohesiveness (i.e., lack of tackiness), integrity of the kernels (i.e., degree of fragmentation), color, flavor, and texture by a taste panel. An optimum preference was expressed by the panelists for those residual kernels resulting from between approximately 4 and 9% weight removal by overmilling.

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11

Properties of the Rice Caryopsis

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INTRODUCTION

Rice is a very important cereal that can be grown under various degrees of flooding (De Datta 1981). It is the staple food of over half the human race and is largely consumed as a boiled, milled grain. Knowledge of the structure and composition of the rice kernel is important to the understanding of its physicochemical and biochemical properties during processing (Bean et al. 1984; Bhattacharya et al. 1978, 1982; Juliano 1980; Lu et al. 1988, 1989).

Detailed ultrastructure of the rice caryopsis (brown rice) has been obtained by scanning electron microscopy (Evers and Juliano 1976; Watson and Dikeman 1977) and transmission electron microscopy (Bechtel and Pomeranz 1977, 1978a,b). Reviews on rice composition and structure have been published by several researchers (Bechtel and Pomeranz 1980; Juliano 1980, 1985). The correlation between physicochemical and functional/nutritional properties of the rice grain has been studied (Juliano 1972a,b, 1977b; Chang et al. 1985; Damardjati 1983; Lii et al. 1984, 1986; Morrison and Nasir 1987; Mosse et al. 1988; Proctor and Goodman 1985).