Effect of Drying on Grain Quality -- Moisture Readsorption Causes Fissured Rice Grains

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ABSTRACT

Among others, drying can affect the quality of rice or other cereal grains (with a hard vitreous endosperm) in three prevalent and distinctive ways. These are:

1. Through Moisture Readsorption by Dry Rice Grains: Rice, as well as other cereal grains, is hygroscopic. The low-moisture (dried) grain readsorbs moisture from any source to which it is exposed. Moisture adsorbed through the grain surface causes the starch cells to expand and produce compressive stresses. Since the grain is a "free body", compressive stresses are countered by equal but opposite tensile stresses at the grain centre. When the compressive stresses at the surface exceed the tensile strength of the grain at its centre, a fissure develops. Fissured grains usually break during milling. Sources for grain moisture readsorption are discussed.

2. Through Moisture Readsorption by Field Rice Grains: When rice grains in the field reach harvest moisture (22%), the field sample may contain grains with moisture contents (MC) between 15 and 45%. Many individual grains may dry to below 15% MC during the day. Such grains can fissure on the stalk when they readsorb moisture at night.

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3. Through Rapid Drying (To near storage moisture): Rapid drying produces a steep moisture gradient in the grain. As this gradient reclines after drying, the grain surface receives moisture from the interior and expands while the grain interior loses moisture and contracts. As this combination of stresses (compressive at the surface and tensile at the centre) develops with time, the grain fails in tension by pulling itself apart at its centre. The rheological aspects (stress, strain and time) that cause the grain failure are discussed.

Most breakage in rice processing can be attributed to grains which were fissured before milling. Moisture readsorption by low-moisture grains in the field before harvest is the most prevalent cause of fissured grains. Mechanical harvesting at a higher moisture content can minimize this type of grain failure. -- Fissuring of the rice grain after drying can be controlled by the drying procedure. Rapid drying which leaves a steep moisture gradient in the grain at the end of drying will cause the grain to fissure after drying. With time the grain fails in tension. Rice drying should not be terminated with a steep moisture gradient in the grain.

Keywords: Rapid drying, head rice, moisture – adsorption, desorption, gradient, stress – compressive, tensile; grain – quality, expansion, contraction.

1. INTRODUCTION

Rice, as all other cereal grains**,** ripens and begins to dry in the field. Ripening of the grains is gradual and progressive and each individual grain cycles daily in moisture content. Lower moisture contents are reached on successive drying days. During the early ripening process, the grain loses moisture only. Later, the grain dries during the day and then may readsorb some moisture at night before continuing the drying process on the following day. When a rice grain dries to below 14 or 15% MC during the day and then readsorbs moisture at night, the grain will/may fissure from moisture readsorption.

2. DEVELOPMENT OF FISSURES IN THE RICE GRAIN

2.1 Through Moisture Readsorption by Dry Rice Grains

The moisture adsorption-fissure concept is not unknown, but is a rather new perception in the rice industry. The commonly prevailing concept has been that the rice grain "sun-cracks" or "sun-checks" as it dries in the field. Sun-cracking of the rice grain was first proposed by Copeland (1924)**.** The sun-crack was defined as a fine cross-wise cracking of the grain caused by rapid drying in the sun. Early crop rice was more subject to sun-cracking than was late crop rice. The term "sun-crack" appeared to be a reasonable explanation for what was happening and was readily accepted throughout the world by the rice industry.

As rice production became mechanized, heated forced air dryers were developed to dry the large volumes of high-moisture harvested rice. Any cross-wise cracking of the grain that was subsequently observed after drying was conveniently referred to as “sun-cracking” of the grain. Hence, the term carried over into mechanized heated forced air drying and is still widely used throughout the world.

In those days, research momentum was being channeled toward rice drying and other initiatives received little support and attention. This is unfortunate because the moisture adsorption-fissure phenomenon was discovered in Japan by Kondo and Okamura (1930). When translated into English, the title of their work is "Fissuring of the Rice Grain from Moisture Adsorption." Their treatise is 19 pages long and probably is the most enlightening, detailed and comprehensive article that has ever been written on the rice moisture adsorption-fissure concept. However, their work was not mainstream research and received little attention in the scientific world for the following reasons: 1) Their work was not widely published and hence was not accessible to many scientists; 2) The mainstream of rice research was on drying; 3) It was published in the German language; and 4) Few post-harvest rice researchers could read German, and therefore were unable to read the article. Even today there still exists the need to translate their work into a more commonly prevailing language and then republish it in one or more technical journals that have a worldwide distribution. Kondo and Okamura summarized their work with eight conclusions. These cannot be repeated here, but can be found in Kunze (1991). Their final conclusion states:

"It is without any doubt that moisture adsorption by the dried grain is the definite cause of fissured grains**.** It follows then that it is very important that dried grains be quickly stored in air-tight conditions to prevent moisture adsorption.”

Thus, the milling quality loss that had been attributed to rice drying was put into its proper perspective, but the information did not permeate the rice drying community in other parts of the world.

The research of Kondo and Okamura (1930) did not go completely unnoticed, because a few post-harvest rice scientists did cite their work. Perhaps the most prominent of these is Stahel (1935), who worked in Surinam. Stahel was unaware of Kondo and Okamura's work while he was doing his own, but then found theirs before he published his works. Stahel’s conclusions followed those that had been drawn by Kondo and Okamura. According to Stahel, the fine cross-wise cracks, which resulted when paddy was remoistened from being left out of doors overnight, were responsible for most of the breakage in milling. Before 1930**,** it was believed that these cracks were due to drying in the sun. But this was not correct. Stahel was unable to produce sun-cracks by drying thin layers of paddy in the sun to less than 10% MC. He dried rice to various MC in the sun and then remoistened the grains to determine at what level the grains would crack from the readsorption of moisture. He found that the initiation of cracks from moisture readsorption varied with variety, but generally occurred when grains had dried to 14 or 15% MC.

Stahel (1935) was also familiar with other previously published rice literature. He took exception to the use of the “sun-crack” term and pointed out that this was a misnomer because the cracks were not due to rapid drying in the sun, but rather to a rise in moisture content.

In the ensuing years, the mainstream of post-harvest rice research continued in the area of drying. Stahel’s (1935) works along with the works of Kondo and Okamura (1930), were slowly and securely buried with volumes of technical rice drying literature. The early concept of sun-cracking never lost its acceptance and then prevailed for three additional decades before being seriously challenged.

As the rice scientists developed and published their research on drying, other scientists were working on the drying of wheat. The literature indicates that there was little if any communication between the two groups even though it would appear that the two cereal grains could have much in common. Few rice researchers cited wheat researchers and few wheat researchers cited work of rice researchers in their journal articles. -- I want to commend the sponsors of this International Conference on Grain Drying for their vision in not restricting the focus of the conference to a single grain, but rather to let the researchers for a given grain share their knowledge and experience with those who are working with other grains**.** Such a conference would have been most beneficial a half century ago and should prove to be of equal benefit today.

Sharp (1927) studied the density of wheat as influenced by freezing, stage of development and moisture content. He found that when the air dried kernel was remoistened it lost some of its density. He proposed that removal of the regained moisture caused "air spaces" to develop in the grain. Some time later, Swanson (1943) studied the effects of moisture on the physical and other properties of wheat. In particular, he was interested in the rewetting of wheat during harvest. Weights taken of test volumes during harvest showed that non-weathered samples at the millers were, on average, 1.81 kg. (4 lb) heavier than weathered samples. He concluded that the swelling from rewetting disturbed the internal compact condition of the grain. He reasoned that after the water was again removed, vacuoles were left in the grain and these decreased its specific gravity and hence its test weights.

The research of Sharp (1927) and that of Swanson (1943) provided the challenge for other researchers to find the “air spaces" or "vacuoles" which these researchers envisioned to develop in the redried wheat. Milner et al. (1950) and Milner et al. (1952) used x-ray techniques to determine internal insect infestation in wheat. This work was followed by Milner and Shellenberger (1953) who studied the physical properties of weathered wheat in relation to fissures detected radiographically. Their observation was that fissures appear because of stresses produced when moisture swollen grains are dried. The weathering (wetting by rain or snow) of unharvested wheat in the field followed by atmospheric drying involved an irreversible decrease in density of the grain. Their discovery of the internal fissures at right-angles to the longitudinal axis of the grain afforded visual proof of the internal spaces in weathered wheat as postulated by both Sharp and Swanson. Their data indicated that cracking occurred when a certain degree or rate of shrinkage of the hydrated endosperm was exceeded. (These scientists at this time – 1953 – were still attributing the development of fissures to rates of drying). Researchers from the same laboratory put the situation into its proper perspective only six years later.

Grosh and Milner (1959) studied the penetration of water into the wheat kernel and the internal cracking which ensued. Their comments are quoted below:

> "Cracks radial and transverse to the crease occurred in the hard vitreous endosperm in advance of water movement through the kernels...Direct evidence that cracks form in wheat as a result of wetting the endosperm alone (tempering) has not been offered previously."

Thus the moisture adsorption-fissure concept was recognized and clearly defined in the rice industry by 1935 and in the wheat industry by 1959. The two groups were not communicating with each other and neither were they communicating with the researchers of other cereal grains that had a hard vitreous endosperm.

After 1935, drying and storage continued to be the primary focus of rice researchers for the decades ahead. Yet if the "truth" is not properly defined and understood, it will continue to surface and tell those who seek it that they have not yet achieved their goal. Subsequent moisture adsorption work was peripheral and incidental. Kik (1951), working in Arkansas, studied the nutritive qualities of rice. He observed that cracks were present in kernels before they were milled and that these kernels were responsible for much breakage during milling. He reported that these cracks resulted from the remoistening of dry rough rice and not from drying too rapidly in the sun. He cited the works of both Kondo and Okamura (1930) as well as that of Stahel (1935). Kik's observation was peripheral to his work and failed to impress those scientists for whom the information should have been meaningful.

As post-harvest rice research continued, few researchers were informed about the research of their colleagues on other continents. Langfield (1957), who published in Australia, reported that "it is well known that much of the grain breakage during harvesting or milling results from fine crosswise cracks that have developed in the grain during the ripening process ... This cracking or checking, which is commonly referred to as sun-checking, results from rapid fluctuations in atmospheric humidity during the ripening process."

Desikachar and Subrahmanyan (1961) in India, also made significant observations on the formation of cracks in rice during wetting and their effect on the cooking characteristics of the grain. Some of their comments follow.

> "Milled or parboiled rice develops transverse lines of cracks when soaked in water. It took a longer time for the cracks to develop in parboiled rice than in raw rice... Rice is very susceptible to this type of cracking during moistening or wetting ... The development of these cracks was dependent on time and temperature of the soak water... The development of cracks on the grain immersed in water seems to be a direct effect of hydration, since the development of these lines is a gradual process and depends on the temperature of the soak water... A certain

> time (about 3 or 4 minutes in the case of raw rice and about 20 minutes in the case of parboiled rice) elapses before the cracking starts which suggests that hydration precedes cracking."

Rhind (1962) also made some observations which give insight into the mechanics that cause the cracks to develop. He states:

> "The highest tensile stresses can be expected in the driest parts, i.e. in the surface layers during drying, but in the inner part of the grain during adsorption ... Grains which are badly cracked are 'destined to break' and do so with a minimum of milling."

Huysman (1965) reported that paddy which is harvested too late will have a great number of sun-cracked grains and that there will be a high percentage of broken rice in the milled product. Sun-cracked percentages found for a given variety of medium grain during 1962-63 were below 10% up to 45 days after flowering with head rice percentages of over 50%. At 50 days after flowering, the sun-cracked percentage increased to 25.5% with a head yield of only 36.8%.

The foregoing is a brief and partial review of moisture adsorption technology in rice and wheat as it can be found in the literature. Yet scientists in the world still seem to be in doubt about the effects of moisture adsorption by a low-moisture (dried) grain. The following was published in the early seventies.

> "Grain development (rice) is essentially complete within 3 to 4 weeks after flowering. Endosperm cracks in rough rice, some researchers claim, result from the contact of the dehydrating caryopsis to liquid moisture such as dew."

The writer of this paper published his first article in 1965. At that time the "sun-cracking from drying" concept strongly prevailed. Fissuring from moisture readsorption was unknown by scientists, engineers and drying experts. The phenomenon was rediscovered through efforts to determine the physical and mechanical properties of rice. The grain could not be fastened into a cylindrical holder with a water-base adhesive without developing a fissure. These efforts were finally discarded and the focus of the work was directed to determine the basis for the development of the fissure or fissures. Grain-ends were ground off to have a flat surface so that the grain would stand on a damp wetted surface such as a wet napkin. Within an hour, the mounted grain developed one or more fissures. This observation caused the title of the proposed research to be changed from a study of the "Physical and Mechanical Properties of Rice" to "Environmental Conditions and Physical Properties Which Produce Fissures in Rice" (Kunze, 1964). Chairman of the Dissertation Guidance Committee was Dr. Carl W. Hall, a member of the National Engineering Academy in the United States. He is world renown for his many books and in particular for his book entitled Drying and Storage of Agricultural Crops (Hall, 1980). More than three decades of moisture adsorption work have followed.

The initial works were published by Kunze and Hall (1965, 1967). The research was with brown rice and was published in the Transactions of the ASAE (American Society of Agricultural Engineers). The work confirmed and also commenced to reintroduce into the literature the works of Kondo and Okamura (1930), Stahel (1935), Kik (1951). and Desikachar and Subrahmanyan (1961). Although all of these references are cited in Kunze (1964), the complete transcript of Kondo and Okamura's work was not found and obtained until August, 1975. The crucial need for it to be translated and distributed to grain drying researchers still exists.

Kunze subsequently pursued the moisture adsorption phenomenon with some difficulty because this concept was controversial (not compatible with accepted technology) and had a low-priority status with financial support sources. However, graduate students from developing countries were interested and wanted to work with rice. They subsequently supplied the expertise and manpower to make it a thriving and productive program.

Kunze and Choudhury (1972) watched the fissures develop as brown and milled rice grains were exposed to a moisture adsorption environment. From these observations, they developed hypothetical stress distributions for both desorption and adsorption of moisture by the grain. Their illustrations show tension at the grain surface and compression in the interior when the grain is drying. Technically these stresses give no justification for the grain to pull itself apart during drying. A tensile failure could logically occur on the grain surface. Adsorption stress distributions showed the grain to be in compression at the surface and in tension at its centre. Whenever the internal tensile stress exceeded the internal tensile strength, there was justification for grain failure (an internal fissure to develop). These stress distributions agree with those proposed by Rhind (1962). Kunze and Choudhury further found that milled rice required only half as much exposure time to produce a fissure as did brown rice. Additional work showed that milled rice in a given environment adsorbed moisture about twice as fast as brown rice. According to Henderson (1972), brown rice dries about twice as fast as rough rice under a given drying condition.

Further research focused on grain fissuring potentials in the harvesting and drying of rice (Kunze and Prasad, 1978). They determined where low-moisture grain may be exposed to a moisture adsorbing environment. Such conditions could exist in the field before harvest, in the combine hopper, field buggy, transport truck, holding bin and in certain dryers ahead of the drying front. McDonald (1967), working in Australia, showed that rice grains on a single panicle in the field may vary in MC by 10 percentage points during the drying process. The variation within a plant could be greater and within a field, the variation could be much greater. Chau and Kunze (1982) and Kunze and Calderwood (1985) found that rice samples with a field moisture of 22% may contain grains between 15 and 45% MC. A freshly harvested rice mass at 22% field moisture has the interstice relative humidity of 97%. The air in a continuous-flow non-mixing heated air dryer enters the wall of grain and becomes humid warm air**.** Low-moisture grains ahead of the drying front may readsorb moisture and fissure before the drying front reaches them.

In developing countries, if cut rice plants are laid out in the field and left too long, the driest and most mature grains may soon fissure from moisture readsorption at night. The drying rice grains may already fissure on the stalk before it is cut. After the rice plants are put into a bundle but then left exposed over night, the little bundle with comparatively more grain exposure will develop a higher percentage of fissured grains than the big bundle with relatively less grain exposure (Kondo and Okamura, 1930).

Dried rice in storage can also fissure from moisture adsorption environments in the tops of storage bins, from aeration and from subsequent transport, shipping and processing operations.

2.2 Through Moisture Readsorption by Field Rice

Much research has been done with rice grains that have been held in a controlled environment storage to maintain grain quality. These rice samples become equilibrated at the given storage conditions and include grains of different maturities. Research with such stored and equilibrated rice grains is good but does not necessarily represent what may happen to grains of different MC and maturities as they are harvested by a combine. The producer needs to know how the grains of different MC and maturities react to their environment and how they react when they are harvested together into a combine hopper or holding bin before being dried.

Kunze et al. (1988) did such work as they studied the influences of fertilization rates on grain production. Highly fertilized plots fruited for a longer period of time and produced a higher yield. On average, grains from the higher fertilized plots dried to a given MC two days after grains from the lesser fertilized plots. On a given day, samples from the higher fertilized plots had a higher MC and fewer fissured grains than samples from the lesser fertilized plots. The percentages of fissured grains from both higher and lesser fertilized plots were essentially the same when both samples had field dried to the same MC. Such moisture levels were reached on different days. Therefore, the final environmental influences could have been different. In general, the conclusion was that the percentage of fissured grains was at the same level when grains from the different fertilization levels reached the same MC in the field.

Rice in the field matures and then proceeds to dry. In the early stages, it looses moisture only but soon reaches the stage where it dries during the day and then readsorbs moisture at night. This drying-moisture readsorption cycle continues from day to day. Stahel (1935) reported that the moisture content of rice standing in the field was 4 to 5 percentage points lower in the afternoon of a dry sunny day than it was at 10 or 11 a.m. Kondo and Okamura (1930) put out rough rice samples at 8 a.m. with a MC of 12.6%. The MC then dropped to 9.5% by 4 p.m., but was back up to 12.4% by 8 a.m. the following morning. No grains fissured while the grains lost moisture (8 a.m. to 4 p.m.) but 72% of the grains fissured while the grains gained moisture (4 p.m. to 8 a.m. the next morning).

When field harvested rice grains are shelled (dehulled), whole and partial fissures can be found in the brown rice. The partial fissures start at the grain centre but do not extend to the outer grain surface. How and why do such partial fissures develop?

As the rice grain begins to dry in the field, it looses moisture only during the day. After several drying days, it continues to dry during the day but then begins to readsorb moisture at night. This drying-readsorption cycle continues during each subsequent drying day. As the grain dries, the magnitude of the cycle increases. The oscillation soon becomes large enough to initiate the moisture adsorption-grain fissure reaction. Moisture adsorption on the grain surface produces compression in the surface cells and tension in cells at the grain centre. When the adsorption stresses at the grain centre (tension) exceed the tensile strength of the grain, a tensile failure occurs. In this period, the grain is transitioning from a rubbery to a crystalline state (Kunze and Calderwood, 2004). This original fissure may be minor and only partially complete, just big enough to be observed. But the drying-moisture adsorption cycle repeats itself each day with rice grains in the field. During every cycle, the grain dries to a lower MC during the day and then readsorbs moisture at night. This repeated cycle causes the partial fissure to grow into a complete or fully grown one.

The foregoing rational seems logical but is not supported by good research data. Such data are desirable but currently not available. Instead of quantitative data, the argument can be supported with qualitative data. When the author was a Rice Process Consultant at the G.B. Pant University (1985) in India, he gave lectures on the moisture adsorption-rice grain fissure response. The lectures were first demonstrated and then the listeners were given the opportunity to have a hands-on experience. The first need was to demonstrate the procedure. If a partially fissured grain was picked for the demonstration, it was often difficult to break. Good, solid, whole grains are hard to break. Fully fissured grains break easily. How could partially fissured grains be eliminated? After some thought, the solution became obvious. Select the fissured grains (partial and fully fissured) to be used. Place these grains into a pedri dish and set them out for one night on a stone wall that surrounded the residence compound. The ensuing night caused the exposed grains to readsorb moisture. The next morning the grains were retrieved with the full assurance that all fissures were complete. All grains would now break easily. Grains were broken in the palm of a hand with thumbnail pressure.

Many rice grains are harvested with such partial fissures. Such grains can complete their fissures in the combine hopper, transport buggy or delivery truck. When a dried grain (crystaline state) is exposed to a moisture adsorption environment, only complete fissures develop which make an audible sound. The fissures in higher moisture field rice grains in the rubbery state may require several drying-moisture adsorption cycles to develop a complete fissure and these produce no sound as they develop.

2.3 Through Rapid Drying

Life would be simpler if a single cause could be attributed to every observed effect; if all fissured rice grains could be attributed to the readsorption of moisture by the grain. This is, however, not the case, because fast drying produces a fissure after drying that is visually the same as the one which results from moisture adsorption. The adsorption fissure develops while the moisture is being adsorbed by the grain. But the fissures which result from rapid drying start to develop shortly after drying and then continue to develop for 48 hours or more. Both grain failures appear to be visually the same and both are equally effective in reducing the milling quality of the grain.

I was in India at the Indian Institute of Technology (IIT) at Kharagpur in 1975. We dried high-moisture paddy in a single pass from 29.8 to 9.1% MC in a column 63.5 CM (25 inches) deep with an air temperature of 59° C (138°F). The procedure was contrary to all established rice drying practices. The initial MC was too high, the drying pass was too long (12 hours), the drying bed was too deep, and the temperature was too high. After drying, the paddy was milled. It gave a total milling yield of 76% and a head rice yield of 74%. Yet after drying and milling, the milled rice grains soon began to fissure and within hours all of them were fissured. The milled rice grains fissured hours after drying. This observation justified further investigation. Fissuring of the rice grain after heated air drying was studied by Kunze (1979). Photographic documentation was used to show that certain grains were not fissured at the end of drying; these grains fissured after drying; a time interval after drying was necessary before the fissures developed; and a fissure does not relieve the stress over a long section of the grain. Several fissures may develop within one grain.

The movement of moisture (in or out) in a rice grain triggers its rheological properties. Rheology is the relationship of stress, strain and time that can be observed in a product. Strength of a material can be expressed, within limits, by stress and strain alone. The rheology of a material is expressed by stress, strain and time; thus indicating that the stress-strain relationship is dynamic and subject to change with time. Such a relationship is evident in rice as it adsorbs and desorbs moisture.

A search of the literature then revealed that Craufurd (1963) working in Sierra Leone, West Africa, appeared to be the first to report the development of fissures in the rice grain after rapid drying. The comments below are from his manuscript,

> "In fast drying of paddy, cracks do not develop until the drying has ceased. Presumably the cracks develop as the moisture gradient within the grain is relaxing ......Since cracks originate at the centre of the grain, they develop while the centre of the grain is losing moisture to the drier outer layers.... In drying it is not the rate at which water is lost from the grain that causes cracking, but some other factor associated with the rate at which the moisture gradient relaxes after drying."

Such information was new in the literature and once again received little attention from rice drying associates. The information was not compatible with that which seemed to be known and did not permeate the rice industries in other countries and continents. But again, it is difficult to keep the "truth" submersed. The work of Craufurd re-emerged and was confirmed by Ban (1971) in Japan. There is no evidence that Ban was aware of Craufurd's work. Researchers in Japan recall that Ban was severely ostracized for his seemingly discordant work; but after his associates returned to their laboratories and confirmed it, they presented him an award. Ban concluded that the cracking does not happen during drying, nor immediately thereafter. Even when the rapidly dried rice was stored under air-tight conditions, an increasing number of cracks appeared for the next 48 hours. Ban gave no explanation for these crack rings (fissures) but proposed that the crack ratio test for dryers in Japan be delayed for 48 hours or more after grains are dried. The observation by Ban was wholly in agreement with that of Craufurd. Milner and Shellenberger (1953), while working with wheat, incorrectly reported that fissuring <u>during</u> the drying process was favored by elevated initial moisture and increased drying rate. Their data suggested that cracking occurred when a certain degree or rate of shrinkage of the hydrated endosperm was exceeded. They further reported that the mechanics of this kind of cracking had been treated thoroughly by Earle and Ceaglske (1949). The work of Earle and Ceaglske with macaroni shows that the cracking occurs after drying. Their comments were (at the end of drying):

> "Where this moisture gradient is large, the macaroni may fail by tension at the inner surface upon the removal of the moisture gradient ...This type of failure is one of the most puzzling to commercial operators, for the macaroni looks and feels strong as long as the drying is in progress. Soon after the fans are stopped the cracking starts."

So the observation of fissuring and cracking after drying by Earle and Ceaglske (1949) with macaroni seems to preempt those of Craufurd (1963), Ban (1971) and Kunze (1979) with rice. They all observed cracking (fissuring) not necessarily during drying but rather after drying. All used a high rate of drying which left a steep moisture gradient in the macaroni or rice at the end of drying. Ironically, their works were uniformly ignored by the then contemporary rice drying scientists.

Further support is given to the fissure after drying phenomenon by more recent researchers. White et al. (1982) studied the development of stress cracks in popcorn as a result of drying and rehydration. Their results agree with those of previous rice researchers who found that stress cracks in rice are caused by a redistribution of moisture after the grain has been removed from the dryer. According to White et al, the delay before the stress cracks occur is related to the moisture gradient existing in the kernel when drying is stopped. Cracks developed during reconditioning of popcorn (moisture adsorption) rather than afterwards, as was found in the drying process. -- After the work of Ban (1971), Nishiyama et al. (1979) developed a crack generation equation to predict the percentage of fissured grains at any time after drying. Kato and Yamashita (1979) worked to minimize the fissures after drying by temporarily storing grains at 60°C. High storage temperatures helped to reduce the development of fissured grains but did not eliminate them.

Sharma and Kunze (1982) also studied post-drying fissure developments in rough rice. A few kernels fissured while drying, but most fissures developed within 48 hours after drying. Some however, did not develop until nearly 120 hours thereafter. Nguyen and Kunze (1984) investigated effects of post-drying treatments on fissures which developed in rice after rapid drying. They reported that an 11% relative humidity and 45°C (113°F) environment engendered fewer fissures in grains than other storage environments which had less tendency to remove surface moisture.

3. NATURE OF THE RICE GRAIN FISSURE

Dry paddy was re-wetted by Craufurd (1963) in an effort to determine where cracks began on or in a rice grain. When whole grain brown rice was placed into water, all cracks which developed were whole cracks and these developed so fast that he was unable to determine their point of origin. Henderson (1954) conducted x-ray studies and showed that cracks (fissures) began at the centre of the grain and then progressed outward parallel to the minor axis**.**

If a physical action occurs with sufficient speed and intensity, it produces a sound. Robert

Young, a graduate student in Agricultural Engineering at Texas A&M University, was the first to record on tape the audible sound made by a grain of popcorn when it fissured from moisture readsorption. Later, Jivo Kouva, Chief of the chemical analysis laboratory of Satake LTD in Saijo (Hiroshima), Japan demonstrated that a low-moisture rice grain produced a sharp audible snap when it fissured. Stermer and Kunze (1992) used a sound transducer to observe the snapping sound on an oscilloscope and subsequently developed an acoustical detection device to record the fissures as they developed in moisture adsorbing rice which was initially at storage moisture.

All of the foregoing information confirms that a low-moisture (dried) rice grain will fissure 1) from moisture readsorption and also 2) after rapid drying (to near storage moisture or below) if the dehydration is stopped with a steep moisture gradient in the grain. The rice grains fissure <u>during</u> moisture adsorption but in the second case they fissure <u>after</u> rapid drying. The second case explains why we have the universal practice of not running milling quality samples immediately after a lot of rice is dried. Instead, we wait as long as practical before doing so. Readsorption of moisture through the surface of a grain after it has been dried rapidly can also cause rice grains to fissure. But the foregoing research indicates that such loss in milling quality develops even if the grains are maintained in an air-tight container. Moisture migration within the grain, as the gradient reclines, is believed to cause these fissures to develop.

Aside from fissures which develop after rapid drying of paddy, we need to identify where low-moisture grains are exposed to moisture adsorption environments. Chau and Kunze (1982) studied moisture content variations among rice grains at the time of harvest. When field rice in a plot was at 22% MC, they found moisture differences up to 29 percentage points between grains (groups of 10) harvested from the tops of the most mature panicles and from the bottoms of the least mature ones. The longer rice at harvest moisture was left in the field, the greater was the probability that lower moisture grains would fissure on the stalk before harvest.

More recently, Sarwar and Kunze (1989) conducted research on RH increases that cause stress cracks in low-moisture corn. They found that grains, equilibrated to 10% MC before being exposed to 75% RH or above, would fissure. All grains fissured when the exposure RH was 92% or above. No grains fissured when the initial grain moisture was 15% or above. Therefore, the moisture adsorption reaction of corn is essentially parallel with that of rice. However, it is perhaps more important that rice maintain its integrity since it is consumed as a whole grain.

Research that moisture adsorption, by low-moisture rice or other cereal grains with a hard vitreous endosperm, produces fissured grains is sufficiently prevalent that it is no longer only a theory. With some exceptions, the phenomenon is accepted today. The moisture can be liquid or vapor. The mainstream of grain drying research is shifting to include the moisture adsorption aspects. The information is becoming useful and is beginning to find application in the grain industries.

4. HISTORICAL SUMMARY

After the mid 1920's, the sun-cracking of rice firmly established itself through four decades of rice drying work. The author of this paper has conducted over four decades of moisture adsorption research and has made the following observations:

1. When the moisture adsorption-rice fissure concept was reintroduced in the 1960's, the phenomenon had to stand by itself; it could not be related to other rice quality research. The rice fissure-moisture adsorption observations were different and therefore separate and apart from other work being done in the rice drying area. Many critical readers were negative on the concept and tended to disqualify the work for publication.

2. Rice research within that period (1960's) had to acknowledge and give credence to the "sun-cracking during drying" concept to get moisture adsorption-grain fissure concepts published. Desikachar and Subrahmanyan (1961) are an example. The following is from their manuscript:

   > The development of checkings or cracks in rice and other grains during dehydration as a result of quick or uneven removal of water is well known, but the occurrence of similar cracks during hydration or wetting is very little understood. Rice is very susceptible to this type of cracking during moistening or wetting.

   Such an acknowledgement was seemingly necessary to make the moisture adsorption-fissure concept acceptable for publication.

3. More recently (2000), the American Society of Agricultural Engineers cited the Rice Fissuring Mechanism Research as "One of the Outstanding Agricultural Engineering Achievements of the 20th Century". The moisture adsorption-rice fissure concept has now been recognized as an accepted truth that needs no other acknowledgements. The original diverse concepts of drying and moisture readsorption have been brought together wherever field rice is being dryed. The drying rice grain experiences both moisture desorpton and adsorption in the field before the grain is harvested.

5. RESEARCH OPPORTUNITIES

One of the needs of the rice industry is for producers, millers and processors to apply the foregoing information to practices. Research to date has provided just enough information to indicate the nature of the grain. But this body of knowledge needs to be expanded by those who work with rice. How long and how fast can rice at a given MC be dried without inducing fissures in the grains after drying? To what moisture content can high-moisture rice be rapidly dried without inducing after-drying fissures? We think that this is 15 or 16% MC. Are these values consistent for all varieties? What treatment or treatments can be developed that will inhibit or prevent fissures in grains after rapid drying? How long can paddy at various storage moistures (10 to 14%) be exposed to various RH (80 to 100%) without developing fissures? We need to better define the moisture adsorption-fissure response in rice types and forms. Can we flash-dry the hull on high-moisture paddy and efficiently shell the grain? Can we flash-dry the bran on the resulting brown rice and mill the high-moisture rice? Can we dry high-moisture milled rice without causing surface cracks in the grain? Can we develop a system that will burn the removed hulls to flash dry the hulls on more high-moisture paddy and then continue to use the heated air to flash-dry the bran on brown rice? Finally, can we use the somewhat humid air to slowly dry the milled rice? Can we make the rice drying industry energy independent by using its own inherent fuel source (hulls)? The foregoing are visions today but they are goals for tomorrow. Team efforts are needed to address these possibilities. The breeders, engineers, producers, dryer operators, storage managers and processors need to work together to bring these visions to an expeditious fruition.

6. RESEARCH APPLICATIONS

Available information now needs to be applied in the rice industry. Jenkins (1989) used a modified harvesting technique where rice panicles were cut and swathed in the field. These panicles were then covered with chopped rice straw to provide protection from the sun during the day and from dew at night. The modified technique showed nearly a 20 point improvement in head rice yield compared to an open windrow treatment. Banaszak and Siebenmorgan (1990) developed data on head rice yield reduction rates caused by moisture adsorption. Kunze et al. (1988) related fissured rice in the field to grain MC, weather and fertilization rates. When rice samples from either fertilization level reached 17 to 18% MC in the field, the proportion of fissured grains subsequently increased very rapidly. Head rice decreases closely followed fissured grain increases.

The body of knowledge on 1) moisture readsorption by storage moisture grains, 2) desorption and adsorption cycles in field rice and 3) the fissuring after rapid drying aspects is being integrated into the grain drying literature and should provide the basis to improve the quality of dried grain. *Field drying and moisture readsorption are inherently related. Drying provides the potential for moisture readsorption that can be very detrimental to grain quality*. Information on the fissuring after drying phenomenon needs to be thoroughly disseminated in the grain industries so that dryer operators, storage managers and grain processors properly understand their processes and procedures, and thereby have the potential to improve them.

A few grains have been observed to fissure during drying. Current concepts of mechanics coupled with the hygroscopic nature of the grain do not justify the development of these fissures. An imperfection in the grain can provide the needed justification. For example, a small surface crack in the endosperm can create an appropriate avenue for fast moisture removal which could cause the crack to grow across the grain into a fissure. Also, this paper does not mean to imply that improperly operated combines, conveyors and processing machines do not have the potential to break grain and reduce grain quality. The energy is there to produce breakage. Operators must diligently seek to keep this damage to a minimum. Equipment and machines which inherently damage grain in their operation will eliminate themselves from the commercial market.

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