HEAD RICE YIELD REDUCTION RATES CAUSED BY MOISTURE ADSORPTION

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ABSTRACT

An empirical rate equation was developed to predict head rice yield reduction for rough rice exposed to moisture adsorptive conditions. Time of exposure, initial moisture content, and relative humidity were significant to the reductions in head rice yield caused by moisture adsorption. An equation used to predict the number of kernels which fissured upon exposure to various environments was modified and evaluated for use in describing head rice yield reductions.

A decrease in head rice yield of greater than 20 percentage points was found in the lowest initial moisture content rice samples (9% wet basis) subjected to the highest relative humidity of 90%. Lower reductions in head rice yield were found in the higher initial moisture content samples and at the lower relative humidity of 70%. Most of the damage to the kernels occurred within the first 24 hours of exposure to the humid air.

INTRODUCTION

A primary goal of the rice industry is to maximize the amount of whole-grain rice (head rice) produced from each unit of rough rice milled. The value of broken rice is often only one-half that of whole-grain rice. In the 1974-1975 season, the economic loss to the U.S. rice industry was estimated to be $115,000,000 (Spadaro and Matthews, 1976). Significant breakage during milling occurs when rice kernels have previously been weakened by stress cracks (fissures) caused by rapid moisture adsorption. These fissured kernels usually break during subsequent hulling and milling operations which results in reduced head rice yields (HRYs).

The observation that low moisture rice kernels fissure from rapid moisture adsorption was reported more than a half century ago by Kondo and Okamura (1930) and Stahel (1935). Their results have been confirmed by Kik (1951), Kunze and Hall (1965, 1967), Kunze (1977), Kunze and Prasad (1978), Chen and Kunze (1983) and Siebenmorgen and Jindal (1986). Chen and Kunze (1983) found that a single exposure of low moisture rough rice to a relative humidity (RH) increase of 30% will cause lower HRYs. Kunze (1988) states that rice samples with moisture contents (MCs) above 14%, before remoistening, generally showed no milling quality loss from the addition of moisture. However, samples which had dried below 14% MC before remoistening showed considerable reductions in HRYs. Kondo and Okamura (1930) and Siebenmorgen and Jindal (1986) cited similar results.

The above studies have indicated the effects of various environments on fissure development and head rice yield reductions (HRYRs). These studies, however, showed these effects after equilibrating samples in a given environment. Limited research has addressed the issue of relating fissure development and subsequent reductions in HRY to the rate of moisture transfer to and from rough rice kernels. The authors have hypothesized that the rate of HRYR is related to the rate of moisture uptake. This article addresses this hypothesis using the experimental results and the associated moisture adsorption model reported in Banaszek and Siebenmorgen (1990).

OBJECTIVES

The objectives of the research reported in this article were to:

1. Determine the effects of initial moisture content (IMC), exposure time, conditioning air RH, and temperature on HRYs of rough rice exposed to adsorptive conditions,
2. Develop an equation to predict HRYRs over time caused by moisture adsorption for the conditions used in this study.

MATERIALS AND METHODS

Newbonnet rice, a long-grain variety, was harvested at the Rice Research and Extension Center, Stuttgart, Arkansas, at approximately 20%*MC during September, 1987 and stored at 1° C for 6 months. The rice was dried in a chamber supplied with air at approximately 20° C with RH set at the desired level according to the Modified Henderson Equation (ASAE, 1987) to attain the desired MCs of 9.0, 10.5, 12.0, 13.5, and 15.0%. All reported MCs are the average of at least three readings of a Motomco 919A† moisture meter which had been calibrated immediately prior to this study using a whole-grain oven procedure reported by Siebenmorgen and Jindal (1987). The relatively slow drying rates, resulting from the use of 20° C air, were used to prevent possible damage due to

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*Unless otherwise specified, all references to moisture content are on a wet basis.

†Mention of a commercial name does not imply endorsement by the University of Arkansas.

drying. After drying, all rice was placed in plastic bags and stored at 1° C until testing. All rice was stored in plastic bags throughout the experiment unless being tested.

Rice was caused to adsorb moisture by placing 450-g samples from the dried lots of rice in trays in a conditioning chamber. The chamber was built to accommodate sixteen, 152 x 254 mm (6 x 10 in.) trays with perforated bottoms placed in parallel above an air plenum. The trays were 150 mm deep with the rice layer being approximately 15 mm thick. Air was supplied to the plenum by a RH and temperature control unit (Parameter Generation and Control 300 CFM Climate-Lab-AA). According to manufacturer's specifications, this unit is capable of maintaining RH within ± 0.5% and dry-bulb temperature within ± 0.2° C. A Phys-Chemical RH and temperature measurement system was used to monitor supply air conditions in the plenum below the samples. After air passed through the samples, it was returned to the control unit to form a closed-loop system. Airflow distribution within the plenum and through each tray was measured with a hot-wire anemometer and was found to be uniform through each tray. The airflow rate through each tray was 1.65 L/s (3.5 cfm).

Experimental Procedure

The experimental design for this study consisted of rewetting rough rice from the approximate MC levels of 9.0, 10.5, 12.0, 13.5 and 15.0% using an airstream at temperatures of 12.5, 20 and 30° C and RHs of 70 and 90%. For each test condition, sufficient rice from one of the five MC lots was removed from storage to load 12 conditioning unit trays. After removal from storage and prior to conditioning, the rice was placed in zip-lock plastic bags and allowed to equilibrate to room temperature of approximately 20° C. Immediately prior to exposure to conditioned air, sample MCs were measured to determine the exact IMC.

The control unit was allowed to reach steady-state operation at a given temperature/RH combination prior to loading samples. The 12 samples were loaded into the conditioning unit with each of the four remaining trays filled with 450 g of "filler" rice. An additional sample was selected to represent the control (time = 0 h). Samples were removed from the conditioning chamber at time intervals of 1, 2, 4, 8, 16, 24, 48, 72, 96, 120, 144 and 168 h from the onset of exposure to the conditioned air. The samples were immediately double-bagged in zip-lock plastic storage bags, placed in cold storage, and MCs determined after at least one week in storage. This storage duration was necessary to allow all kernels to fully equilibrate from the kernel surface to the interior. After samples were removed from the conditioning unit, filler rice was placed in the trays to maintain a uniform airflow rate through all trays. The resulting moisture adsorption curves are presented in Banaszek and Siebenmorgen (1990).

Since it is common practice to conduct HRY determinations using rice at a moisture level of approximately 12.5%, all samples which attained a moisture level greater than 12.5% were subsequently dried in the conditioning unit to approximately 12.5% MC using an air condition of 20° C and 60% RH. Samples with moisture levels below 12.5% were milled at their respective MC level.

Determination of HRY consisted of selecting duplicate 150-g subsamples from the original 450-g conditioned sample. The samples were dehulled using a McGill huller with a clearance of 0.048 cm (0.019 in.) between rollers. The resulting brown rice was milled for 30 s using a McGill No. 2 miller. Separation of the brokens from whole kernels in the milled sample was performed using a Seedburo sizing machine. Whole kernels (head rice) are defined as "unbroken kernels of rice and broken kernels of rice which are at least three-fourths of an unbroken kernel" (USDA, 1983). The HRYs of the two subsamples from each sample were averaged for subsequent analysis.

Results and Discussion

HRYR Tests

The HRYR data for rice exposed to the various airstreams used are shown in figures 1 through 4. The curves represent estimates of HRYR as calculated by an equation presented below. For some of the temperature/RH/IMC combinations, the airstream was not moist enough to cause adsorption by the rice. Only the samples in which moisture adsorption occurred were milled. Thus, for many of the temperature/RH conditions, only curves associated with the lower IMCs are presented. Further, the temperature/RH combination of 12.5° C/90% RH was not obtainable with the control unit in the ambient conditions in which it was located.

In figures 1 through 4, the vertical axis, 'Head rice yield reduction', is the difference between the HRY of the control (time = 0 hours) and the HRY of the sample at the corresponding time on the horizontal axis. The following discussion and analysis of HRYR is based on the first 24 hours of data. This time limit was chosen since practically all of the damage that occurred took place within 24 hours of exposure.

Figure 1 displays the HRY response of rice to air at 30° C and 90% RH. The 9.04% IMC level resulted in the greatest reduction in HRY. After just 2 hours of exposure, the HRY decreased by 13 percentage points. The HRY had decreased by 20 percentage points within 24 hours. This corresponds to a price reduction of approximately $1.50 per cwt, based on the 1984 average dockage rate of $0.075 per cwt per percentage point of HRYR (Fryar et al., 1986). The HRYR at the 10.32% IMC level was not as drastic as

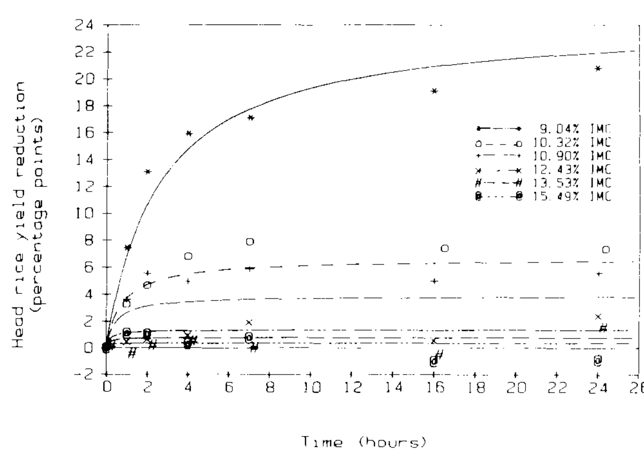

Figure 1–Experimental data and head rice yield reduction curves (eq. 1) for rough rice exposed to an airstream at 30° C and 90% RH.

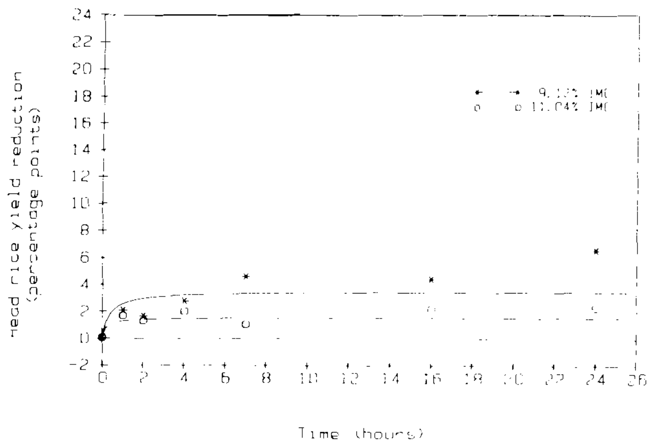

Figure 2–Experimental data and head rice yield reduction cures (eq. 1) for rough rice exposed to an airstream at 30° C and 70% RH.

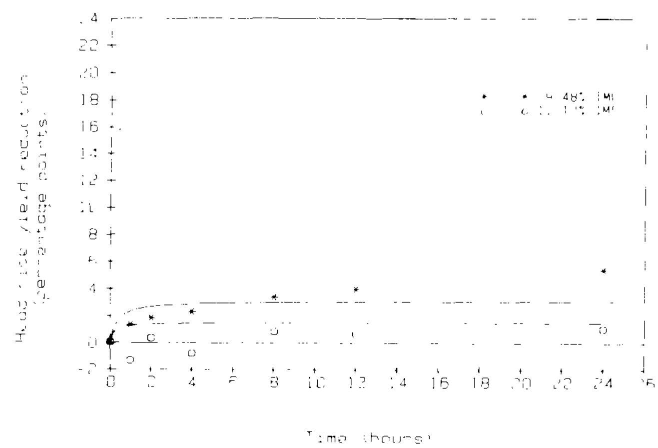

Figure 4–Experimental data and head rice yield reduction curves (eq. 1) for rough rice exposed to an airstream at 20° C and 70% RH.

that of the 9.04% IMC level, yet the reduction was still significant. After 24 hours of exposure, the HRY decreased by 7 percentage points for the 10.32% IMC level and 5 percentage points for the 10.90% IMC level. The remaining IMC levels resulted in HRYR of 2 percentage points or less within 24 hours. Thus, as IMC was increased, the resulting damage caused by moisture adsorption was less severe. It also appears that for these air conditions, damage due to moisture adsorption was not severe unless rewetting was initiated at MCs below approximately 12%.

Similar trends but with much less drastic results of HRYR are shown in figure 2, which illustrates the adsorptive condition of 30° C and 70% RH. After 24 hours of exposure, HRY decreased by approximately 6 percentage points and 2 percentage points for the 9.12% IMC and 11.04% IMC levels, respectively. Thus, in comparing Figs. 1 and 2, moisture adsorption reduced HRY much more at the higher RH level.

Figures 3 and 4 display the response of rice to air at 20° C/90% RH and 20° C/70% RH, respectively. The trends discussed previously also apply for these conditions as well as the 12.5° C/70% RH condition which is not shown. An interesting finding when comparing results within the 70% RH or 90% RH levels was that the HRYR due to temperature was not large. This observation is supported by the regression analysis discussed in the next section.

HRYR Equation

The first equation analyzed for use in describing the data was of empirical nature and was selected based on the trends of the data matching the curves presented by Hoerl (1954). The selected equation had the following form:

$$HRYR = t / (a + b * t) \qquad (1)$$

where

HRYR	=	HRY reduction (Ho - Ht), %,
Ht	=	HRY at time t, %
Ho	=	HRY of control (time = 0 h) %,
t	=	time, h,
a, b	=	regression coefficients.

The NLIN least squares procedure from SAS (1987) was used to fit this equation to each HRYR curve. The GLM procedure (SAS, 1987) was used to show that both parameters, a and b, were significantly different between curves at a significance level of 5%.

The next step was to relate IMC, RH, and temperature to the a and b parameters in equation 1. The REG procedure from SAS (1987) was utilized in a stepwise approach to develop equations to predict a and b values for all conditions. The resulting equations from the analysis were:

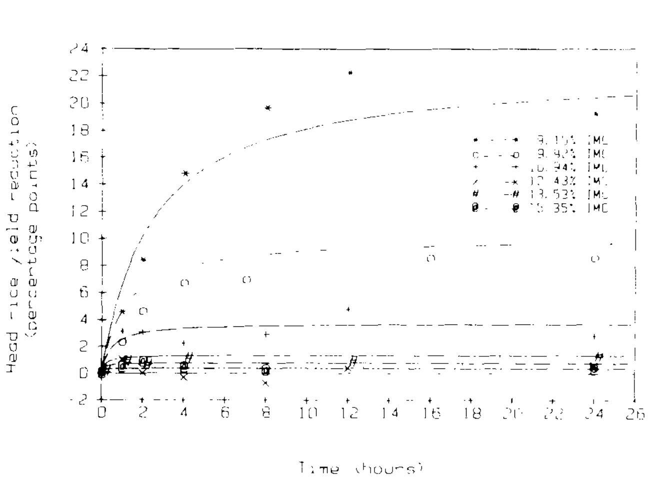

Figure 3–Experimental data and head rice yield reduction curves (eq. 1) for rough rice exposed to an airstream at 20° C and 90% RH.

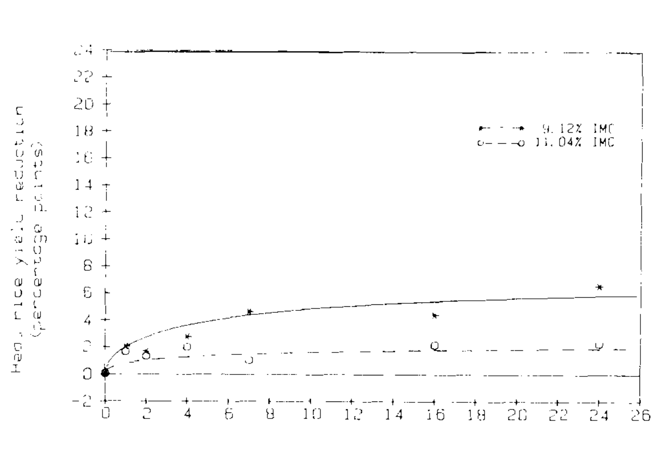

Figure 5–Experimental data and head rice yield reduction curves (eq. 5) for rough rice exposed to an airstream at 30° C and 70% RH.

$$a = a_2 * IMC \quad (2)$$

$$b = a_3 * IMC^2 + b_3 * IMC^2 * RH + c_3 * IMC^3 + d_3 \quad (3)$$

where

IMC = initial moisture content, % wet basis,
RH = relative humidity, decimal,
a_2, a_3, b_3, c_3, d_3 = regression coefficients.

The absence of temperature as an independent variable in equations 2 and 3 supports the earlier observation that temperature was of minimal importance in reducing HRY. Equations 2 and 3 were substituted into equation 1 and the NLIN procedure from SAS was used to obtain new estimates for all regression coefficients. The regression coefficients and model statistics are listed in Table 1. The resulting error mean square (MSE) for equation 1 was 1.398. Although the MSE seems somewhat high, the authors feel that the model predicts HRYRs sufficiently well considering the inherent variability in HRY determinations from sample to sample. The curves in figures 1 through 4 were generated using equations 1 through 3 with the values of the regression coefficients listed in Table 1.

TABLE 1. Regression coefficients and statistics for the head rice yield reduction equations [equations 1 and 5]

Equation 1: $HRYR = \frac{t}{a + b * t}$

where: $a = a_2 * IMC$
$b = a_3 * IMC^2 + b_3 * IMC^2 * RH + c_3 * IMC^3 + d_3$

For use in predicting actual (non-adjusted) head rice yield reductions:

a_2 = 0.011674512	$s(a_2)$ = 0.001167451	MSE = 1.398
a_3 = -0.027676183	$s(a_3)$ = 0.010494436	
b_3 = -0.014427232	$s(b_3)$ = 0.001785737	
c_3 = 0.003100051	$s(c_3)$ = 0.000724150	
d_3 = 1.073776072	$s(d_3)$ = 0.322123916.	

For use in predicting head rice yield reductions adjusted to a common milling moisture content of 12.5%:

a_2 = 0.016139540	$s(a_2)$ = 0.001905187	MSE = 0.921
a_3 = -0.133817105	$s(a_3)$ = 0.043348439	
b_3 = -0.064283263	$s(b_3)$ = 0.020172603	
c_3 = 0.014121525	$s(c_3)$ = 0.002762957	
d_3 = 5.289553289	$s(d_3)$ = 1.150273828.	

Equation 5: $HRYR = (Ho - He) * (1 - \exp(-k * t^n))$

where: $k = a_6 * RH * IMC * T$
$n = a_7 * RH * IMC * T + b_7 * RH$

For use in predicting actual (non-adjusted) head rice yield reductions:

a_6 = 0.001930166	$s(a_6)$ = 0.000133177	MSE = 0.705
a_7 = -0.002420495	$s(a_7)$ = 0.000594553	
b_7 = 1.473759364	$s(b_7)$ = 0.150834430.	

For use in predicting head rice yield reductions adjusted to a common milling moisture content of 12.5%:

a_6 = 0.001736610	$s(a_6)$ = 0.000158213	MSE = 0.551
a_7 = -0.004208780	$s(a_7)$ = 0.000608711	
b_7 = 1.91816004	$s(b_7)$ = 0.186962743.	

An Alternative HRYR Equation

A "crack generation" equation was used by Nishiyama et al. (1979) and by Sharma and Kunze (1982) to describe the number of kernels which fissured upon exposure to various environments. This equation was also modified and evaluated for use in describing HRYRs. Since the rate of fissure development is hypothesized to be related, at least in part, to the rate of moisture adsorption, this equation was thought to have physical significance. After being modified to incorporate HRY instead of number of fissured kernels, the equation had the form:

$$\frac{Ht - He}{Ho - He} = \exp(-k * t^n) \quad (4)$$

where

He = lowest, asymptotic HRY obtained during test, %
t = time, h
k,n = regression coefficients.

For ease in comparing the statistics of equations 1 and 4, equation 4 was first rearranged with only Ht remaining on the left hand side. Both sides of the equation were then subtracted from Ho in order to resemble the left hand side of equation 1, which resulted in the form:

$$HRYR = (Ho - He) * (1 - \exp(-k * t^n)) \quad (5)$$

The lowest, asymptotic HRY obtained for each IMC level/test condition combination was assumed to be the equilibrium HRY (He).

The regression procedure used for equation 1 was again used for equation 5. The regression coefficients for k, as well as the coefficients for n, were found to be significantly different between all curves. The equations developed for the k and n parameters had the form:

$$k = a_6 * RH * IMC * T \quad (6)$$

$$n = a_7 * RH * IMC * T + b_7 * RH \quad (7)$$

where

T = temperature, °C,
a_6, a_7, b_7 = regression coefficients.

The resulting coefficients and model statistics are listed in Table 1. The resulting MSE for equation 5 was 0.705. In terms of MSE, equation 5 is better than equation 1 in predicting HRYRs caused by moisture adsorption. Equation 5, however, is restricted to applications in which an He is known corresponding to a given Ho. Thus, unless an He is known or until future research develops an adequate model to predict He for given environmental and IMC conditions, the authors believe equation 1 is the preferred equation, at this time, for use in predicting HRYR due to moisture adsorption. The curves in figures 5 and 6, which display the HRYRs at the air conditions of 30° C/70% RH and 20° C/90% RH, respectively, were generated using equation 5 to show how well this model fits the data if He is known. Estimates of He can be determined using equation 1 for subsequent use in equation 5. However, this approach introduces additional error compared to that of using only equation 1 to predict HRYR. The resulting MSE of equation 5 was 1.575 when estimates of He were determined using equation 1, compared to an MSE of 1.398 when solely using equation 1 to predict HRYR.

ADJUSTMENT FOR LOW MCs AT MILLING

Results of several studies (Banaszek et al., 1989; Webb and Calderwood, 1977; Pominski et al., 1961) have shown that milling rice in a laboratory miller at differing MCs produces accordingly different HRYs. In general, as the MC at milling decreases, the HRY increases. This behavior during milling represents an imperfection in the determination and comparison of HRYs. There is no standard, approved method for adjusting HRYs to account for differences in the MC at milling. This is due in large part to the fact that if rice is delivered at a MC less than 12.5%, it is generally milled at the delivered MC and is not rewetted to the 12.5% level. Based on findings of the above studies, HRYs obtained in this study could have been affected by milling at different MCs as well as by moisture adsorption. Since all samples that reached a MC above 12.5% were subsequently dried to 12.5% MC prior to milling, the effects of MC at milling primarily concerns those samples that had a MC of less than 12.5% at the time of milling.

An effort was made to remove the effects of milling at different MCs from the HRYs obtained in this study. This effort used the results of an earlier study (Banaszek et al., 1989) in which the effects of milling rice at various MCs were quantified. This earlier study used the same lot of harvested rice used for the present study. The equation developed from this earlier study that describes the HRYs attained over the range of MCs used is

$$HRY = -0.130873 * MC^2 + 1.199528 * MC + 61.248997 \quad (8)$$

where

HRY = head rice yield, %,
MC = moisture content at milling, % wet basis.

The adjustment procedure consisted of using equation 8 to calculate the HRYs that would have been attained when milling non-rewetted rice at the sample MCs obtained in this study. The difference between these calculated HRYs and the HRY obtained with equation 8 using a MC at milling of 12.5% resulted in the necessary adjustments to be subtracted from the actual HRYs determined in this study. The HRYR was calculated as was done previously. This procedure thus adjusts all HRYRs to a common milling MC of 12.5% with the resulting adjusted HRYRs being due only to moisture adsorption.

The regression procedure described previously was again applied to equations 1 and 5 using the adjusted HRYR data. The resulting regression coefficients and model statistics are listed in Table 1.

Figure 7 displays the HRYRs adjusted for MC at milling for the condition of 20° C and 90% RH. To prevent overlapping of curves, only the four lowest IMCs are shown. A comparison of figs. 3 and 7 shows that HRYR was significant at the two lowest IMCs even after adjustment for milling at different MCs. The results at the condition of 30° C and 90% RH followed similar trends as those of fig. 7. All adjusted HRYRs for the 70% RH conditions were generally two percentage points or less.

Adjustment of HRYs to a common milling MC depends on the application. From an experimental standpoint, it is desirable to partition the effects of moisture adsorption and MC at milling. However, adjustment of HRYs to a common MC necessitates knowledge of the effects of milling at different MCs, such as that given by equation 8. Banaszek et al. (1989) showed that this relationship can be affected by rice variety and storage condition and is thus not universal. Further, an inherent assumption of the adjustment procedure used above was that the relationship between MC at time of milling and HRY can be applied to rice which was milled after being exposed to treatments such as moisture adsorption.

From the standpoint of representing actual HRYRs, it could be desirable not to adjust HRYs due to MCs at milling being less than 12.5% since HRYs of samples milled at less than 12.5% are typically not adjusted for MC. The lack of an approved adjustment procedure for experimental comparisons also could preclude adjusting HRYs. Thus, because of the pro and con arguments for adjusting HRYs, the constants of equations 1 and 5 are listed for both adjusted and non-adjusted cases in Table 1.

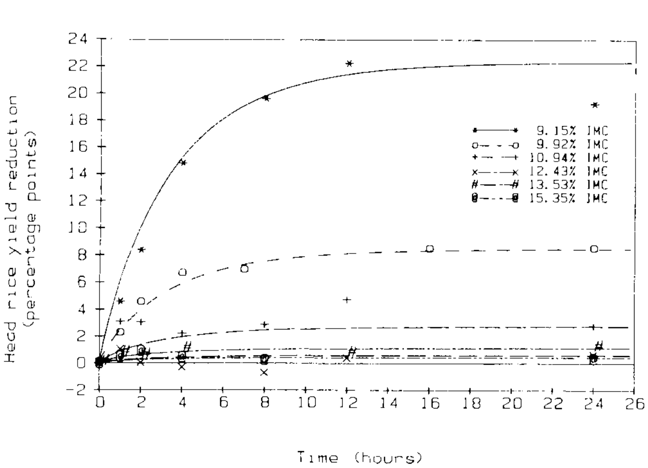

Figure 6–Experimental data and head rice yield reduction curves (eq. 5) for rough rice exposed to an airstream at 20° C and 90% RH.

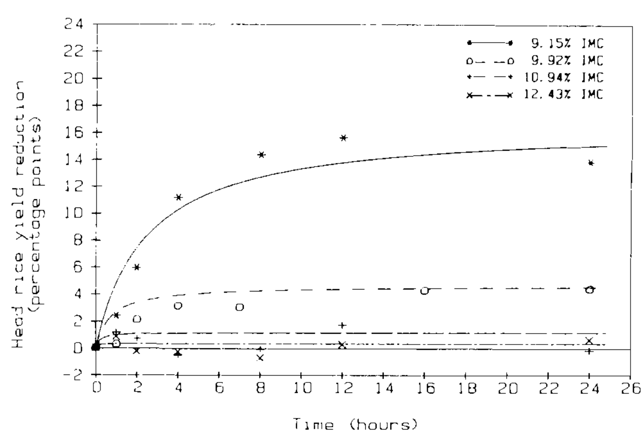

Figure 7–Experimental data and head rice yield reduction curves adjusted to a common milling moisture content of 12.5% (eq. 1 with adjusted coefficients) for rough rice exposed to an airstream at 20° C and 90% RH.

HRYR Rate

To obtain the rate of HRYR (non-adjusted for MC at milling), the partial derivative of equation 1 with respect to time was used:

$$\frac{d\ (HRYR)}{d\ (t)} = \frac{a}{[a + b * t]^2} \qquad (9)$$

where

a = equation 2,
b = equation 3,
t = time, h.

Rate of HRYR curves were generated using equation [9] and are shown in figures 8 and 9. Figure 8 displays the HRYR rates for various levels of IMC at a base condition of 30° C and 90% RH. As was expected, the lowest IMCs produced the highest rates of HRYR. Increasing the IMC level correspondingly decreased the rates of HRYR. For the IMC levels of 12% and 13.5%, the HRYR rates were small in comparison to the lower IMC levels. The 9% IMC level in figure 8 showed a HRYR rate of 1 percentage point/h at a time of 6 h, whereas with the higher IMC levels, the reduction rates had reached near minimum within 6 h.

Figure 9 shows the effect that RH has on HRYR rates at a base condition of 9% IMC and 30° C. At the 90% RH level, the rate of HRYR is initially high and decreases exponentially. The 70% RH level resulted in a similar trend but with much less drastic results. The 90% RH level shows HRYR rates which were at least 5 times greater than the 70% RH level for the first 10 hours. The rates appear to converge after 24 hours of exposure.

Effects of Adsorption Rate on Head Rice Yield

To relate the effects of adsorption rate on HRYR, a moisture adsorption equation from Banaszek and Siebenmorgen (1990) and equation 1 were utilized to generate the curves presented in figure 10. The curves presented in figure 10 represent HRYR (non-adjusted for MC at milling) as a function of average adsorption rates for 1 hour intervals at the condition of 30° C and 90% RH. Average adsorption rates were calculated as follow:

$$\text{Average Adsorption Rate} = \frac{\%MC\ (t+1) - \%MC\ (t)}{1\ \text{hour.}}$$

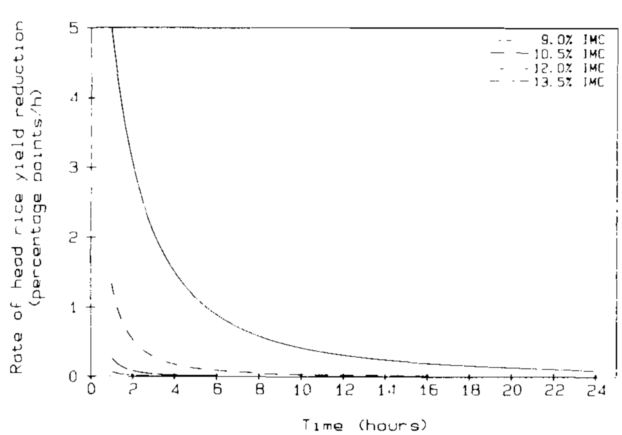

Figure 8–Rate of head rice yield reduction as affected by initial moisture content at the condition of 30° C and 90% RH.

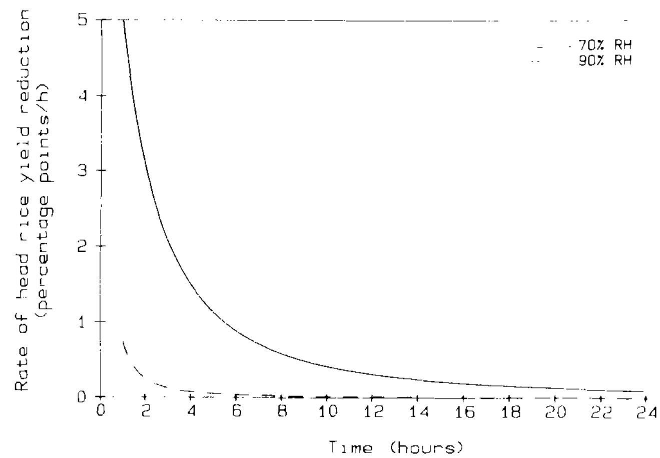

Figure 9–Rate of head rice yield reduction as affected by relative humidity at the condition of 9% IMC and 30° C.

The first point at the right of each curve represents the first hour interval. The lowest IMC of 9% resulted in the highest average adsorption rate (1.6% MC/h) and associated HRYR (7 percentage points) during the first hour. During the second hour, the average rate of adsorption decreased significantly but resulted in an additional HRYR of 4 percentage points. As the IMC level was increased, the corresponding average adsorption rate and HRYR for each time interval decreased. For a given average adsorption rate, there was no single level of HRYR. Thus, it appears that not only is HRYR a function of adsorption rate, but it is also a function of the moisture level corresponding to that rate.

Summary and Conclusions

Head rice yield data obtained in this study showed RH and IMC to be significant contributors to HRYRs caused by moisture adsorption. Temperature was found to be of minimal importance in reducing HRY under adsorptive conditions. The high RH level of 90% and low IMC of 9% resulted in a HRYR of over 20 percentage points, the highest reduction measured in this study. The HRYRs at the 70% RH level and IMCs of 12.5% and above were not nearly as severe as those of the 90% RH level and IMCs

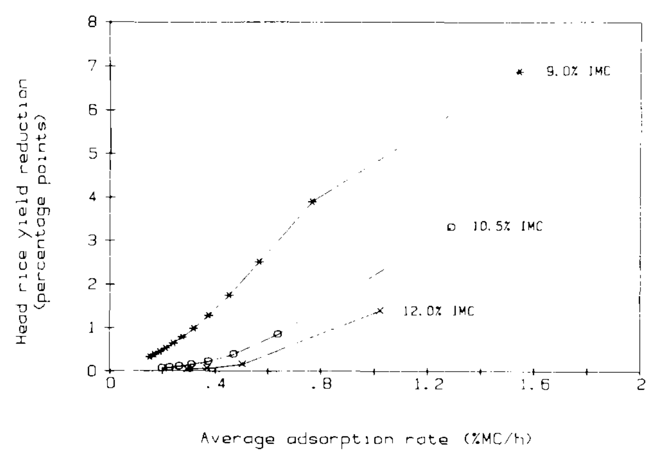

Figure 10–Head rice yield reduction as affected by adsorption rates for 1 h intervals at the condition of 30° C and 90% RH.

below 12.5%. Practically all reductions in HRY had occurred within 24 h of exposure at all test conditions.

An empirical equation was developed to predict HRYRs caused by moisture adsorption for the conditions of this study. Considering the inherent variability in HRY from sample to sample, the model adequately predicted HRYRs for the conditions tested. Additionally, an equation developed to predict the number of fissured kernels was previously modified and evaluated for use in describing the HRYRs of this study. Using estimates of He from the data, this model predicted HRYRs well. However, the use of this equation is limited in that an He is required.

At the base condition of 9% IMC and 30° C, the rate of HRYR was at least 5 times greater at the 90% RH level as compared to the 70% RH level for the first 10 h of exposure. For the IMC levels of 12% and above, the HRYR rates were small in comparison to the lower IMC levels.

High adsorption rates resulted in high HRYRs. The magnitude of the HRYR was shown to be a function of a given moisture adsorption rate and IMC level.

REFERENCES

ASAE Standards, 34th ed. 1987. Standard D242.3. St. Joseph, MI: ASAE.

Banaszek, M.M. and T.J. Siebenmorgen. 1989. Modeling moisture adsorption characteristics of rough rice. ASAE Paper No. 89-6528. St. Joseph, MI: ASAE.

Banaszek, M.M., T.J. Siebenmorgen and R.N. Sharp. 1989. Effects of moisture content at milling on head rice yield and degree of milling. Arkansas Farm Research 38(2): 15. University of Arkansas, Fayetteville.

Chen, Y.L. and O.R. Kunze. 1983. Effects of environmental changes on rice yield and particle size of broken kernels. *Cereal Chemistry* 60(3): 238-241.

Fryar, E.O., L.D. Parsch, S.H. Holder and N.P. Tugwell. 1986. The economics of controlling peck in Arkansas rice. Arkansas Farm Research. May-June 35(3): 7. University of Arkansas, Fayetteville.

Hoerl, A.E., Jr. 1954. Fitting curves to data. In *The Chemical Bus. Handbook*, ed. John Perry, 1 (Sec. 20): 55-77. New York: McGraw Hill.

Kik, M.C. 1951. Nutritive studies of rice. Agricultural Experiment Station Bulletin 508, Univ. of Arkansas, College of Agriculture, Fayetteville.

Kondo, M. and T. Okamura. 1930. Der durch die feuchtigkeits zunahme verursachte querris (Doware) des reiskorns. Ber. d. Ohara Inst. f. Landwirtschaftl. *Forschungen* 4: 429-446.

Kunze, O.R. and C.W. Hall. 1965. Relative humidity changes that cause brown rice to crack. *Transactions of the ASAE* 8(3): 396-399,405.

———. 1967. Moisture adsorption characteristics of brown rice. *Transactions of the ASAE* 10(4): 448-450.

Kunze, O.R. 1977. Moisture adsorption influences on rice. *Journal of Food Process Engineering* 1(2): 167-181.

Kunze, O.R. and S. Prasad. 1978. Grain fissuring potentials in harvesting and drying rice. *Transactions of the ASAE* 21(2):361-366.

Kunze, O.R. 1988. Simple R.H. systems that fissure rice and other grains. ASAE Paper No. 88-5010. St. Joseph, MI: ASAE.

Nishiyama, Y.,M. Satoh and H. Shimizu. 1979. Crack generation of rough rice after drying. Iwate University, Japan. *Journal of the Faculty of Agriculture* 14(3): 277-288.

Pominski, J., T. Wasserman, E.F. Schultz, Jr. and J.J. Spadaro. 1961. Increasing laboratory head and total yields of rough rice by milling at low moisture levels. *Rice Journal* 64(10): 11 .

SAS Institute Inc. 1987. SAS/STAT Guide for Personal Computers, Ver. 6 ed. Cary, NC: SAS Institute Inc.

Sharma, A.D. and O.R. Kunze. 1982. Post-drying fissure developments in rough rice. *Transactions of the ASAE* 25(2): 465-468, 474 .

Siebenmorgen, T.J. and V.K. Jindal. 1986. Effects of moisture adsorption on the head rice yields of long-grain rough rice. *Transactions of the ASAE* 29(6): 1767-1771.

———. 1987. Effects of oven drying temperature and drying time on rough rice moisture content determination. *Transactions of the ASAE* 30(4): 1185-1192.

Spadaro, J.J. and J. Matthews. 1976. The economic impact of rice breakage. In *Proc. 16th Rice Technical Working Group*, Lake Charles, LA.

Stahel, G. 1935. Breaking of rice in milling in relation to the condition of the paddy. *Trop. Agriculture* 12(10) : 255-260.

USDA. 1983 (Rev.). United States Standards for Rice. Federal Grain Inspection Service, U.S. Department of Agriculture, Washington, D.C.

Webb, B.D. and D.L. Calderwood. 1977 . Relationship of moisture content to degree of milling in rice. *Cereal Food World*. Vol. 22, 484 pp.