Moisture Exchange Determined by a Conductance Meter in Single Kernels of Corn Blends

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ABSTRACT

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Moisture was determined in single kernels of wet and dry and rewetted blends. Determination by conductance involves the use of an instrument with a pair of piercing needles. The digital readout can be connected directly to a computer and mean percent moisture and standard deviation of the mean of single kernels computed automatically. The instrument was used to determine distribution of moisture among individual kernels or heterogeneity in blends of corn ranging widely in moisture content. The rate of equilibration of moisture in individual corn kernels was affected by their mechanical damage. The rate of moisture exchange and heterogeneity of equilibrated and freshly blended samples, as assessed by determination of moisture in individual kernels, was followed at 24-hr intervals for up to 168 hr. Blending of samples varying widely in moisture content could be established for up to seven days in some commercial corn samples.

The problems associated with blending corn, which varies widely in moisture content, are well recognized. They include hazards of mold infection in wet samples and breakage susceptibility in over-dried samples. In well-mixed and aerated samples, the moisture equilibrium can be reached quickly and depends on many factors such as hardness of corn kernels, mechanical and heat damage, size and shape of kernels, and differences in moisture of blend components.

We have published a series of papers on the determination of moisture in mixtures of dry and wet corn (Pomeranz and Czuchajowska 1986; Martin et al 1986, 1987, 1988). The moisture of equilibrated and freshly blended corn mixtures was measured with a Tag-Heppenstal (T-H) conductance meter. The meter was connected to a digital oscilloscope equipped with a magnetic disk memory to record signals from the T-H roll electrodes. The recorded signals were analyzed to determine the standard deviation (SD) around the mean percent of moisture. Two SD measurements were made for each signal: the base SD of the signal when no corn was present between the electrodes, and the SD of the signal (mV) when corn was passed between the electrodes. A fast Fourier transformation was performed for about 2 sec of the mid-SD of the signal; an inverse function reconstructed the digitally filtered signal. For each measurement, three subsamples of 100 g were used. Each subsample required 2–3 sec to pass between the roll electrodes. The SD of the equilibrated corn depended on the level of broken corn and foreign material (BCFM) in the sample and the extent of mold and heat damage. Freshly blended samples approached equilibrium at an exponential rate. After 48 hr it was impossible to tell if the samples were blended or not. In freshly blended corn we could detect as little as 7.5% of wet corn, by weight.

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The main advantages of the previous method were simplicity and speed combined with a small sampling error. The main limitations were that the information was obtained on an average of 20 kernels tested at one tine. The objective of this study was to determine the rate of moisture exchange in individual kernels of equilibrated, freshly blended, and rewetted samples. In addition we studied the effect of mechanical damage on the rate of exchange.

MATERIALS AND METHODS

Materials

The present study was conducted with yellow dent corn obtained from three sources: five commercial corn samples of unknown history from Iowa (oven moisture 8.5–13.9%); six commercial corn samples with an unknown history from the Standardization Division, Federal Grain Inspection Service (FGIS), Kansas City, MO (oven moisture 10.3–13.9%); and four corn samples with a known history from the Grain Marketing Research Laboratory (GMRL) in Manhattan, KS (oven moisture 10.3–15.3%). The Iowa and FGIS samples were combine harvested; two of the GMRL samples were hand shelled and two were combine harvested.

FGIS commercial samples and known combine-harvested hybrids (GMRL) were evaluated for breakage (mechanical damage) by the method of Chowdury and Buchele (1976). A representative portion, about 100 g, of each sample was treated with the fast green dye to aid visual separation of breakage categories. Description of breakage categories, as percentage by weight, is shown in Table I.

We removed BCFM (fraction D1) from all samples before applying the green dye. In commercial samples high in BCFM (up to 10%), the small particles can absorb water very fast and become moldy.

Methods

Moisture was determined in single kernels by electrical conductance. A picture of the instrument is shown in Figure 1 and of the instrument scheme in Figure 2. The instrument consists of several components. First is a pair of piercing needles, which are inserted into the kernel. The two needles, 1.5 mm long and 1.5 mm apart, were made from 0.4-mm thick stainless steel wire. The spacing of the needles is critical. If the needles are too far apart, the conductance is too low to measure. If the needles are too close, it is difficult to obtain a satisfactory average value of a kernel's moisture. The optimum spacing was determined after a long series of experiments. The longer the needles, the larger the volume of kernel tested. Long needles, however, break or bend easily and can break the kernel. While the needle diameter is not critical, too thick needles are difficult to insert into dry or round kernels (the latter represent about 2% of the total). If the needles are damaged or broken and replaced by a new pair, a new calibration curve must be obtained.

As the needles are inserted, they push the kernel against a thermistor that measures kernel temperature. The needles and the thermistor are connected by cable to a CR-10 data logger, a microprocessor-controlled, programmable data gathering device. The data logger was programmed to control and read the signal from the needles inserted into the kernel. In addition, the microprocessor was programmed to convert the conductance reading to percent moisture.

The kernel moisture is measured as follows: the needles are inserted about 1 mm deep, on the side opposite to the germ, through the pericarp into the horny endosperm. In the case of very tiny kernels they are pushed even into the floury endosperm. After the needles are pushed into the kernel, and moisture is encountered, a voltage potential develops across R1 (Fig. 2), interpreting the high moisture as a (near) short across the probes. When the probes encounter low moisture, an infinite resistance across the probes pushes the value of R2 nearest to the value of 1K, developing the voltage across both R1 and R2. The internal software of the data logger interprets these voltage potentials and converts them into a moisture reading.

Individual kernels were manually placed in the holder of the instrument, and the two small needles were mechanically inserted into each kernel. A mechanical device to continuously process a large number of kernels is being developed. The needles were wired to a microprocessor. The potentiating voltage was passed through the kernel and the electrical conductance was measured between the needles. The conductance was then calibrated against well-equilibrated kernels of known moisture, as determined by the 72 hr, 103°C oven method (ASAE 1983). The moisture readings of kernels in a sample were averaged and the SD was calculated automatically.

Three sets of well-equilibrated samples were used for calibration. Low-moisture (below 13%) samples were kept at room temperature for at least one year in sealed 1-gallon jars filled almost to the top. Samples with 13 to 16% moisture were stored for 1 year at 4°C. Corn with moisture greater than 16% was obtained by adding appropriate amounts of water. After water was added, the samples were stored in sealed 1-quart jars filled with 500 g of grain for one day at room temperature and for at least two months at 4°C. Well-equilibrated, hand-shelled flat corn samples with low mechanical damage were used for calibration. First, oven moisture was determined by the ASAE (1983) method on duplicate 15-g bulk samples. Next, moisture was determined in individual kernels by the same oven procedure (103°C, 72 hr). If oven moisture of individual kernels showed a standard deviation of up to 0.3, the sample was considered equilibrated. The moisture reading of this sample was logged into the instrument memory. Then, instrument and oven moisture readings were compared. Moisture differences of up to 0.4%, on the average, were considered acceptable.

Several experiments were conducted on blends of wet and dry corn from the samples described above. We present the results of three blends in which 30% wet corn and 70% dry corn was used to obtain 14% moisture in the mixture. In experiment I we used a hand-shelled hybrid BoJacx603 at 10.30% moisture as the dry component and at 21.37% moisture as the wet component. In experiment II we used the hand-shelled BoJacx603 at 21.37% moisture as the wet component, and the commercial corn from FGIS with 10.80% moisture and ~60% mechanical damage, as the dry component. The third blend (experiment III) was obtained by mixing hand-shelled Pioneer hybrid 3377 at 21.14% moisture and an FGIS sample at 10.85% moisture and ~50% damage.

Blended samples were kept at room temperature (22 ± 2°C). The blends were obtained by mixing ~500 g of corn (dry and wet) in tightly sealed quart jars filled to about 10 cm headspace; 200 individual kernels were used each time for moisture determination by the moisture meter; then the whole sample was used for oven moisture determination. All determinations were made in duplicate. The measurement were made at 4-hr intervals on the first day after blending and at 24-hr intervals, up to 168 hr, thereafter. In addition, experiments I and II were run by mixing 60-g samples (about 200 kernels) of dry and wet corn. For each

TABLE I
Breakage Damage Categories of Corn

Breakage Category	Description
D1 Fine	Passed through a 4.76-mm round hole screen
D2 Severe	Less than ½ kernel broken
D3 Moderate	More than ½ kernel broken
D4 Minor	Whole kernel with cracked pericarp or endosperm
D5 Minimum	Whole kernels, no easily visible mechanical breakage

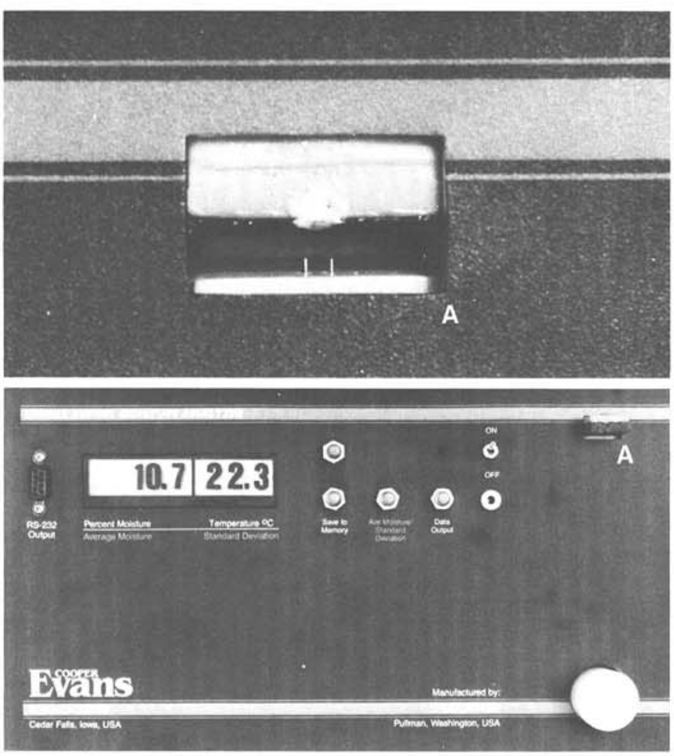

Fig. 1. Picture of single kernel moisture testing device. Bottom: instrument panel with pair of piercing needles indicated (**A**). Top: magnified detail of needles. Instrument dimensions 32.0 × 18.0 × 9.5 cm. Distance between needles 1.5 mm.

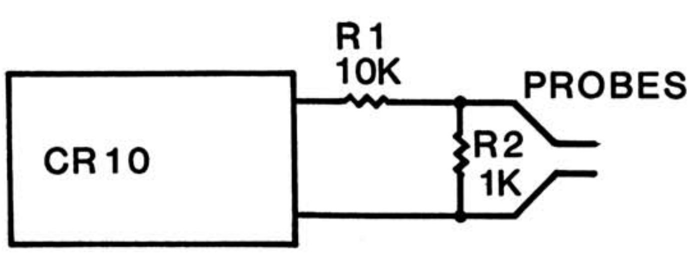

Fig. 2. Schematic of single-kernel moisture testing device and piercing needles (probes); details presented in text.

measurement, blends were kept at room temperature in 100-ml jars. In those experiments, the whole sample was used for moisture determination by the conductance method and next by the oven moisture method. For the latter, the sample was divided among three cups (about 20 g in each).

The final experiments were carried out to establish the rate of water penetration into corn kernels (wetting experiment). Water was added to the hand-shelled corn sample (BoJacx603) and to the highly mechanically damaged commercial corn (from FGIS, 60% damage). In both cases, water was added to increase the moisture from 10 to 14%. Moisture was determined in 200 kernels (each) 3, 8, 12, 24, 32, 48, and 72 hr after the addition of water. Water was absorbed much more rapidly by the commercial corn than by the hand-shelled corn (data not shown). Three hours after water was added, the mean moisture of individual whole kernels was 2.5% higher, and of individual commercial corn kernels 1.3% higher, than calculated. The mean moisture of the individual kernels from the commercial sample after 8 hr showed no change, but the mean moisture of whole kernels decreased gradually.

RESULTS AND DISCUSSION

Percentages of broken kernels in two of the commercial FGIS samples and in one combine-harvested corn (BoJacx603) from the

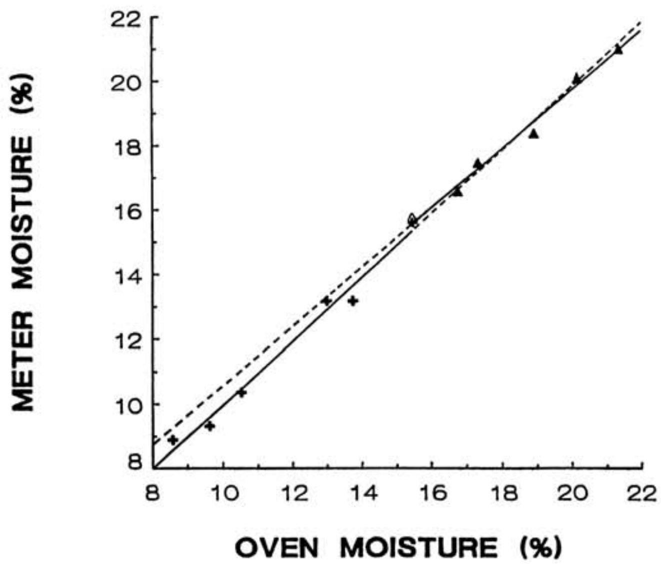

Fig. 3. Calibration of single-kernel moisture testing device vs. oven moisture for the low (+) and high (▲) moisture ranges. Solid lines are based on linear equations of experimental data; broken lines are based on extrapolation of the above lines.

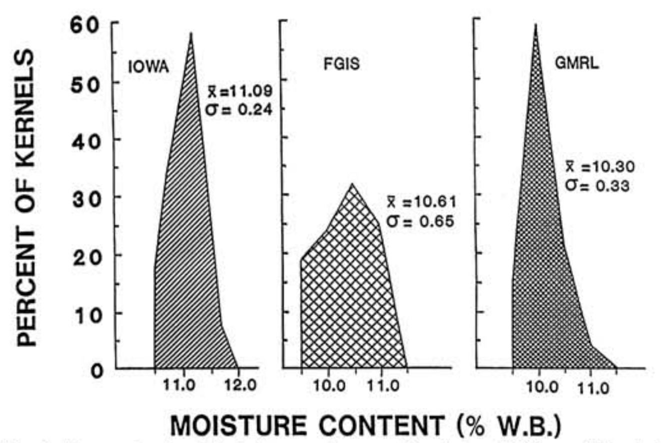

Fig. 4. Mean, standard deviation, and range of moisture (%) in equilibrated corn kernels from Iowa, Federal Grain Inspection Service (FGIS), and Grain Marketing Research Laboratory (GMRL) low-moisture samples; y-axis = percent of total number of kernels in a sample.

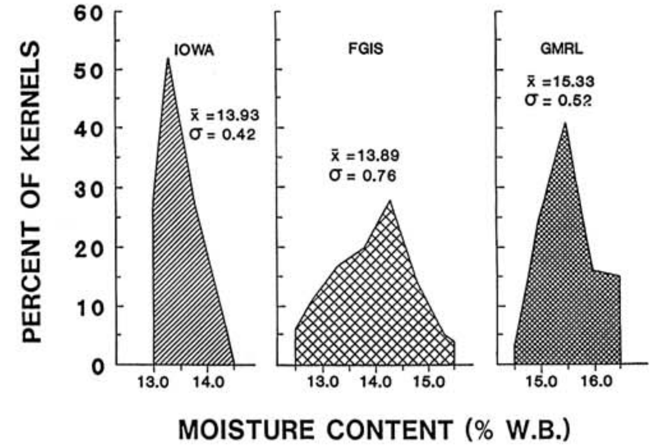

Fig. 5. Mean, standard deviation, and range of moisture (%) in equilibrated corn kernels from Iowa, Federal Grain Inspection Service (FGIS), and Grain Marketing Research Laboratory (GMRL) high-moisture samples; y-axis = percent of total number of kernels in a sample.

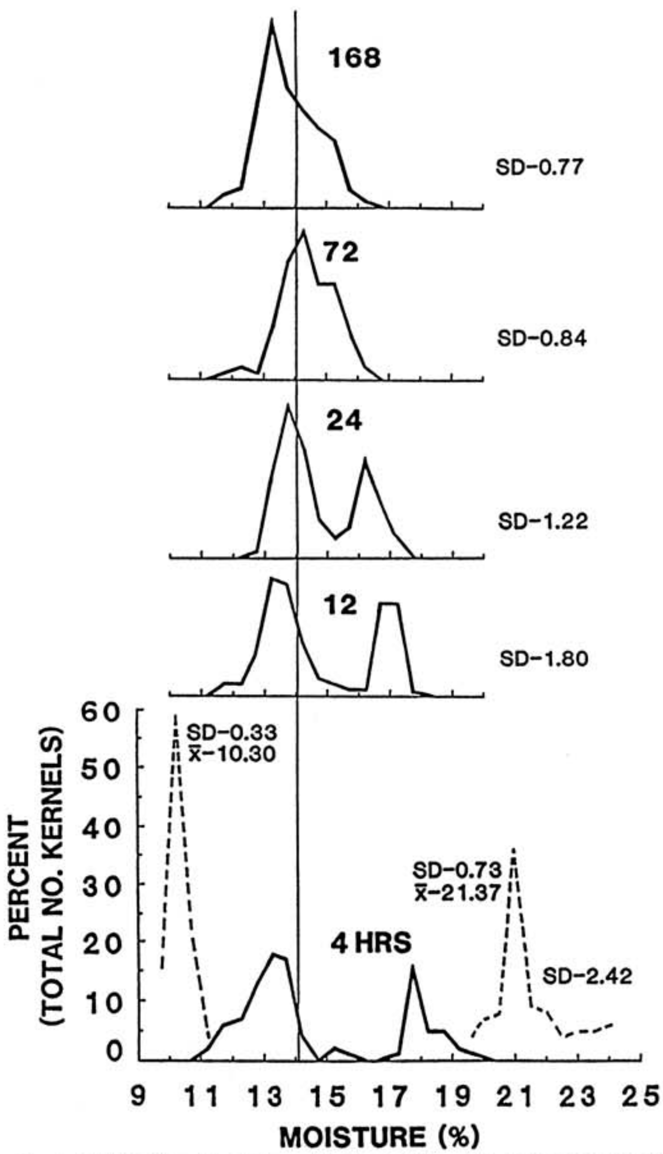

Fig. 6. Distribution of moisture after storage for up to 168 hr in a blend of corn from experiment I. Broken lines: equilibrated original two lots of the corn blend; solid lines: blends of the original two lots after 4, 12, 24, 72, and 168 hr, respectively; vertical line: mean oven moisture (14%). The y-axis represents, in each case, percent of total number kernels in a sample and is drawn to the same scale for the blends after 4, 12, 24, 72, and 168 hr. Data for 48, 96, 120, and 144 hr not shown.

GMRL varied widely. Whereas the BoJac sample had over 80% whole kernels (D5), percentages of visually undamaged, whole kernels in the two FGIS samples were about 50 and 40%, respectively.

Figure 3 shows linear correlations between instrument and oven moisture ranges of 8.5–15.5% and 15.5–22.0%. Depending on the moisture level of a particular kernel, the instrument switched automatically from one prediction equation to another. The linear regression lines and correlation coefficients for the low moisture range were $y = 0.977x + 0.051$, $r = 0.992$, and for the high moisture range $y = 0.917x + 0.234$, $r = 0.994$, where y = meter moisture and x = oven moisture. The correlation coefficient for the total range was $r = 0.997$.

Moisture in all equilibrated samples was determined both by the oven method and the moisture meter. One hundred kernels were used for each measurement, in two replications per sample. The distribution of moisture in equilibrated samples from different sources and their ranges of moisture, as measured by the single-kernel method, are summarized in Figures 4 and 5.

In the well-equilibrated samples, the ranges of moisture in single kernels are narrow and the SDs are low (Fig. 4). In samples from Iowa and GMRL, over 90% of the kernels had moisture levels of maximum ±0.5% around the mean. In the sample from FGIS, which represented highly damaged corn, there was a wider range of moisture and a higher SD value.

In all samples, a high level of moisture produced a high SD (Fig. 5). The highest SD value for the equilibrated samples was recorded in one of the FGIS samples, indicating that the sample had already been blended.

In experiment I both components were sound, hand-shelled, corn of known history; 4 hr after blending the moisture ranged from 11 to 19% with two peaks of 13 and 18% moisture originating from the wet and dry components. The SD was also high (Fig. 6). These peaks were clearly visible until 48 hr. After 72 hr it was not possible to tell, based on the shape of the curves, which corn was blended and which was not; still the SD was higher than for the two original corn samples in the blend.

In experiment II, the wet corn component was the same as in experiment I but the dry component was different (results not shown). We expected in this case, in which highly damaged corn from FGIS was used, that water would penetrate fast and therefore it would be difficult to determine whether the corn was blended. After 12 hr the SD was lower than in experiment I. After 72 hr the two peaks were still noticeable, and 168 hr after blending the SD was higher than in experiment I after the same time. The reason for the unexpected results could be that the commercial FGIS sample was in part moldy and heat damaged, and that the transfer of moisture from the sound wet whole kernels to the damaged dry kernels was very slow or irregular at best.

Experiment III is another example of using a commercial damaged corn as the dry component. Several days after blending, a wide range of moisture with two peaks was present; the SD was above 1 (Fig. 7). In the freshly blended corn one could detect as little as 1–5% wet corn within 3 hr after blending (calculated from data in another experiment not shown here, similar to the one used to plot Fig. 7). Thus, blends in which dry corn samples include grain of unknown history and drying conditions may be characterized by a wide moisture range even 168 hr after blending.

Figure 8 compares the percentage of kernels in the narrow moisture range from 13.5 to 14.5% in the samples of the wetting experiment described previously. Only 8 hr were required for 50% of the commercial corn kernels to reach that range; only 8% of the whole kernels were in that range after 8 hr. Even after 72 hr, less than 50% of the hand-shelled BoJacx603 kernels were in the 13.5 to 14.5% moisture range. Thus, in whole undamaged kernels, moisture penetration was slow whether water was added or blends of dry and wet kernels equilibrated.

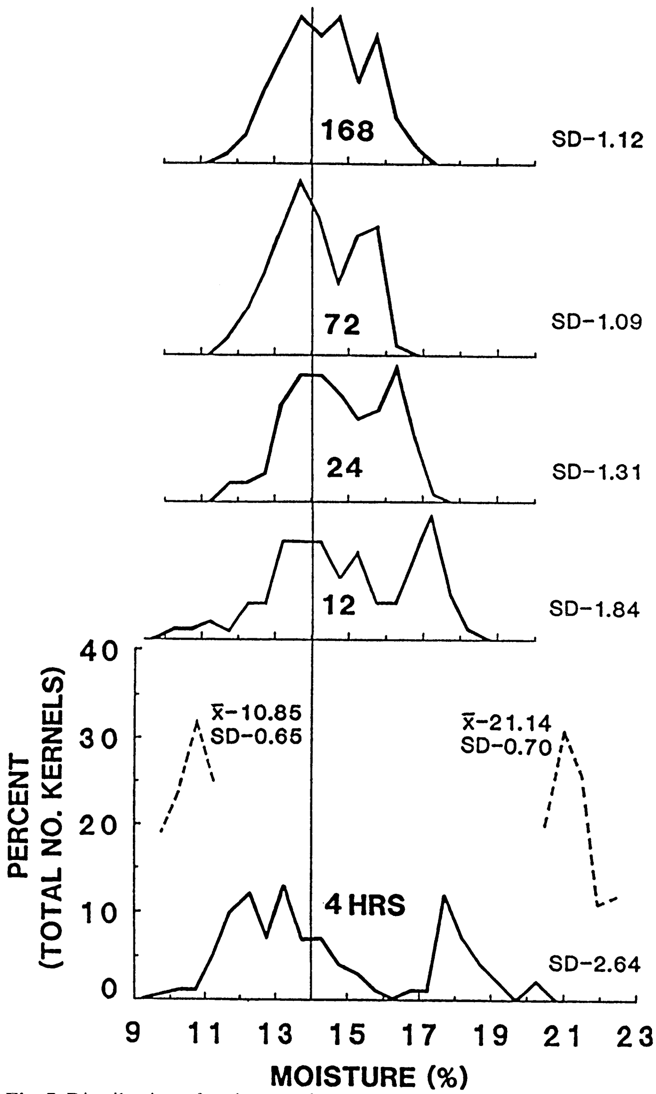

Fig. 7. Distribution of moisture, after storage for up to 168 hr, in a blend of corn from experiment III. Broken lines: equilibrated original two lots of the corn blend; solid lines: blends of the original two lots after 4, 12, 24, 72, and 168 hr, respectively; vertical line: mean oven moisture (14%). The y-axis represents, in each case, percent of total number of kernels in a sample and is drawn to the same scale for the blends after 4, 12, 24, 72, and 168 hr. Data for 48, 96, 120, and 144 hr not shown.

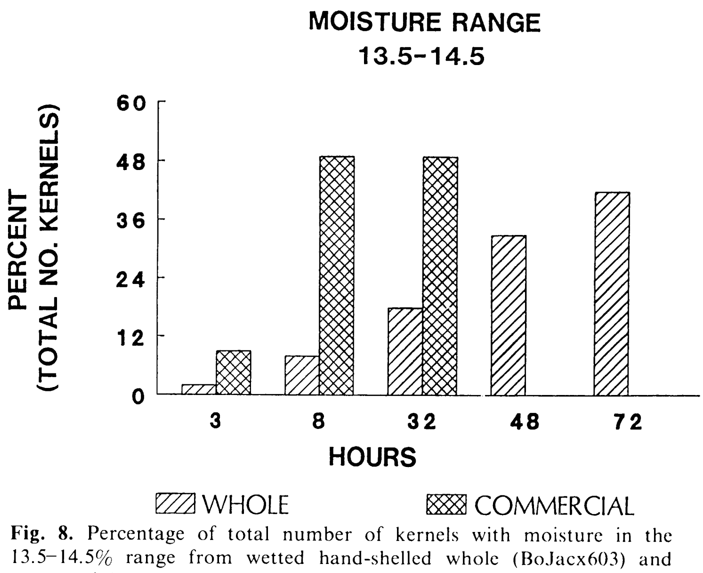

Fig. 8. Percentage of total number of kernels with moisture in the 13.5–14.5% range from wetted hand-shelled whole (BoJacx603) and commercial (Federal Grain Inspection Service, 60% damage) corn equilibrated for 3, 8, 32, 48, and 72 hr, respectively.

TABLE II
Comparison of Heterogeneity Parameters in Equilibrated Corn

Corn Sample Description and Source	Moisture (%) Range	Moisture (%) Mean	SD	Heterogeneity Factor
Low moisture				
Iowa	10.5–12.0	11.09	0.24	5.0
FGIS	9.5–11.5	10.61	0.65	6.0
GMRL	9.5–11.5	10.30	0.33	6.0
High moisture				
Iowa	13.0–14.5	13.93	0.42	8.0
FGIS	12.5–15.5	13.89	0.76	10.0
GMRL	14.5–16.5	15.33	0.52	7.0

TABLE III
Comparison of Heterogeneity Parameters in Corn Blends

Corn Sample Description	Moisture Range (%)	SD	Heterogeneity Factor
Experiment I			
24 hr	12.5–17.5	1.22	18.2
168 hr	12.0–16.5	0.77	11.0
Experiment II			
72 hr	12.0–16.0	0.95	12.5
168 hr	12.0–16.0	0.91	10.0

CONCLUSIONS

The single-kernel meter provided information on moisture distribution during blending of wet and dry corn. Within 48–72 hr moisture equilibration takes place, but the rate and pattern varies between hand-shelled sound kernels and commercial damaged kernels. The difference is particularly noticeable in the rate of moisture penetration into wetted corn. The information provided by the instrument is similar, in part, to that of a determination based on grinding 20 kernels at a time (Martin et al 1987). However, the single-kernel instrument can provide additional important information (other than SD) about the extent and nature of heterogeneity of blended and equilibrated samples. We used the data to determine an arbitrary heterogeneity factor, Hf, which was defined (Pomeranz et al 1988) as follows:

$$\mathrm{Hf} = \frac{\begin{array}{c}\Sigma \text{ absolute differences between moisture contents}\\ \text{(of kernels sorted according to increasing moisture)}\\ \times \text{ range of moisture contents}\end{array}}{\text{percent of moisture contents at maximum}}$$

Heterogeneity factors were computed in three samples of equilibrated low-moisture corn (Fig. 4) and three samples of equilibrated high-moisture corn (Fig. 5). The results are summarized in Table II. The low-moisture equilibrated samples had different SDs but comparable Hfs. The high-moisture equilibrated samples were all higher in Hf than the corresponding low-moisture samples.

We also compared standard deviations and Hf in 24- and 168-hr old blends of corn (experiment I, Fig. 6), which had similar ranges of moisture but widely different standard deviations, and in 72-and 168-hr old blends of corn (experiment II), which had similar ranges of moisture and similar standard deviations. The results are summarized in Table III. The large differences between the 24- and 168-hr samples in experiment I (Fig. 6) are reflected both by differences in SD and Hf. The large differences between the 72- and 168-hr samples in experiment II are reflected by differences in the Hf but not in the SD. Whereas the 72-hr sample shows a bimodal population, the 168-hr samples show a fairly uniformly blended equilibrated corn sample. It is of interest that both equilibrated corn samples from FGIS (Table II) were comparable in SD but differed widely in Hf. The high-moisture FGIS sample (Table II) was the only one that had an Hf comparable to that of samples blended (and probably incompletely equilibrated) in the laboratory (Table III). The high-moisture FGIS sample also had the widest range of moisture and probably was a blend corn that varied widely both in moisture and post-harvest handling.

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