MODIFICATION OF THE STRONG-SCOTT BARLEY PEARLER FOR WHEAT HARDNESS TESTS

by

DENNIS K. KUHLMAN

B.S., Kansas State University, 1970

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1975

Approved by:

Major Professor

ACKNOWLEDGMENT

The United States Department of Agriculture and the Department of Agricultural Engineering, Kansas State University, provided the facilities, assistance, and financial support for this investigation. Thanks is given to Dr. C.A. Watson and Mr. Ralph McGinity of the U.S.D.A. Grain Marketing Research Center and Dr. William H. Johnson, Head of the Department of Agricultural Engineering, for their support and guidance in carrying out this research.

Special acknowledgment goes to Dr. Do Sup Chung, major professor, for his thoughtful encouragement and direction. The author wishes to thank the other members of the graduate committee, Dr. T.O. Hodges and Dr. J.C. Annis, for their assistance.

THIS BOOK CONTAINS SEVERAL DOCUMENTS THAT ARE OF POOR QUALITY DUE TO BEING A PHOTOCOPY OF A PHOTO.

THIS IS AS RECEIVED FROM CUSTOMER.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A_o = Constant

M_o = Mass of starting material at time zero

M_t = Mass of unbroken starting material left at time t

K_u = Size modulus

B = Constant

r = Size ratio

t = Time

p.f.= Power factor

Tp = Pearler torque

h = Chart height

Ep = Pearling energy

Cp = Value indicated by pearlograph integrator unit

Epw= Pearling energy indicated by wattmeter

S10= Number 10 Tyler sieve particle oversize

S14= Number 14 Tyler sieve particle oversize

S20= Number 20 Tyler sieve particle oversize

PAN= Pan sieve - all remaining fine particles

PTQ= Pearlograph peak torque

PWT= Pearler peak watts

AAP= Pearlograph area - total energy

AAW= Pearler wattmeter area - total energy

PLI= Pearling index

BDN= Bulk density

TDN= True density

KWT= 1000 kernel weight

PCT= Protein content

MYD= Milling yield

INTRODUCTION

The hardness of wheat is not only of scientific interest but also of great commercial importance. During the storage and transportation of grain from the field to the commercial processor, there is a large amount of mixing of varieties, growing locations, and other factors until the grain received by the commercial processor is unidentifiable as to processing quality. Also as grain is a complex capillary-porous body consisting of natural polymers, there will be a variation of hardness from kernel to kernel within a single variety. An index for wheat hardness probably has little meaning or value in itself. Its importance would necessarily depend on: how well it correlates with other indexes of quality such as protein content, sedimentation value, flour yield, starch damage, or percent vitreous kernels; its range of values for correctly classifying wheat with respect to millability; and its capability of estimating approximate power consumption and milling costs (Greenaway, 1969).

The problem of testing wheat hardness dates back almost to the beginning of milling. Numerous attempts habe been made to develop a method or machine to give reliable results of determining wheat hardness. These methods have ranged from the primitive test of chewing small samples and measuring hardness from the reactions of human sense to hard or soft kernels to the most elaborate mechinical systems. In spite of considerable research efforts, a satisfactory hardness measurement has not been developed.

For economic reasons, millers (processors) are interested in a simple but reliable testing instrument to determine the hardness of wheat. Hard wheat requires more power to mill and also causes more wear and repairs on milling equipment. An accurate hardness tester would enable millers to estimate milling power and repair costs for a particular wheat sample. It would also make standardization of milling procedures possible throughout the milling industry. The flour from the mills could be designated as to their relative qualifications for baking uses, as hard wheat flours are generally used for breads while soft wheat flours are used for pastry purposes.

Many types of instruments have been used to determine wheat hardness. The decision as to which instrument modification offered the best approach to the problem was not an easy one to make. The basic approach used for this study was to make an extensive survey of the literature regarding hardness measurement. Then an effort for improving the operational procedures, machine operation and output was made by a modification of the Strong-Scott barley pearler, for wheat hardness tests.

REVIEW OF LITERATURE

General Concepts of Wheat Hardness

Wheat hardness is defined as the resistance of kernels to deformation by external forces. Kernel hardness has been measured as a means of assessing the mechanical properties of cereal grains. An acceptable method of measuring kernel hardness has been the object of a great deal of interest and investigation in connection with grading, classifying and identifying the type of grains for a particular use. Most instruments designed to test wheat hardness have an abrasive, crushing, grinding or cutting action. Those selected for laboratory work should be sturdy, rapid and simple to operate (Greenaway, 1969). Any scientific method of wheat grading must be of great rapidity of operation in order to be of practical commerical value (Roberts, 1910). In addition, they should lend themselves to standardization so that results among laboratories agree.

For economic reasons, millers are interested in reliable, quick, simple methods to determine wheat hardness that would be applicable to plant operations. Hard wheat requires more power to mill, causes more roll repairs and sieve replacements than softer wheat. However, wheat that is too soft does not mill well and produces low flour yields (Greenaway, 1969).

Wheat quality laboratories are constantly trying to improve their methods of evaluating the merits of new varieties.

Plant breeders want to produce a grain that has high protein content but is not exceptionally hard. Milling quality has presented many problems to these laboratories arising from the many factors entering into its evaluation and the difficulty of measuring these factors accurately with laboratory milling equipment. Poor milling quality is a function of rate milling, optimum milling moisture, total flour yield, yield of patent flour and ash content of patent or straight grade flour. All are interrelated and an accurate measure of one is dependent upon existing conditions of the remaining factors (Seeborg, 1953).

Wheat varieties differ in the ease with which kernels can be converted to flour; hardness is one factor influencing this. The miller desires a high total flour yield, a good yield of patent flour and a low ash content in his product (Popham, et al. 1961). An easy efficient test to help the miller obtain the correct type of wheat to produce the best possible product is desirable. Also a hardness test would be helpful in determining the amount of grain conditioning needed to bring milling capability to an optimum condition and if possible, to improve the baking quality of a grain lot (Smeets and Cleve, 1956).

Discussion of Hardness Tests

The hardness of wheat grains have been approached from many angles. Two equations express the integral rate at which fines are produced from a homogeneous material in a grinding process (Mular, 1962):

$$\frac{M_o - M_t}{t} = A_o \, K_u^{B} \qquad (1)$$

or

$$\frac{M_o - M_t}{t} = A_o \, X_o^{\gamma} \, r^{-\gamma} \qquad (2)$$

where

A_o= constant

M_o= mass of starting material at time zero

M_t= mass of unbroken starting material left at time t

K_u= size modulus of the portion (M_o-M_t)

B = constant that is generally equal to the distribution modulus

$\frac{(M_o-M_t)}{t}$ = the integral rate at which fines are produced from a parent material

r = size ratio which varies with time and is a function of the input

X_o= size of unfractured parent

t = time

γ = B/2

Equation 2 suggests that the actual energy expended per unit mass to fracture that mass is proportional to the number of breaks produced raised to some power. It has been demonstrated by Mular (1962) that the Graudin-Meloy (1962) distribution for single fracture (a distribution based on the assumption that a random fracture of a homogeneous material produces daughter particles of similar shape) is equally applicable to multiple fracture and is related to the Gaudin-Schuhman (1960) distribution (a distribution yielding the cummulative fraction finer than any size, X) at least when the distribution modulus is close to unity. The quanity, $A_o X_o$ was found to be independent of starting mass over the range studied when particle size was held constant. The above equations are related to the input energy to the grinding mill. This input energy concept of determining wheat kernel hardness can be used with both the Brabender Hardness Tester (BHT) and a modified Barley Pearler, but the value of K_u is extremely variable for wheat kernels.

The meal granulation test described by Cutler and Brinson (1935) may best be adapted for use by the wheat breeder. It serves as a dependable aid in identifying the low protein hard or yellow hard wheat that, though relatively low in protein, are too granular for manufacture into satisfactory pastry flours. Evidence has been presented by Cutler and Brinson (1935) which suggests that the granulation of the wheat meal is highly stable varietal characteristic. However, the granulation test does not appear to be a good hardness indicator.

Some researchers used devices which allowed measurement of the resistance of cutting kernels under controlled loading conditions. One apparatus of this kind is the Murbimeter (Chapon, 1963). The wheat sample is fed into a hopper from which kernels roll down on a plate having a hollow wide enough to take up one kernel. The kernel in the plate is pushed steadily against one or two needles, and the resistance of compression is measured by a calibrated spring. The force required to cut off the kernel is electrically classified on one of six counters according to the range of force encountered. According to Mepplink (1968), the instrument indicated an inconsistancy of wheat hardness and is sensitive to kernel size. In an attempt to improve the Murbimeter, a new device called the Temnometer was designed. The mechanism of this device indicates the position of loading weight on a balance beam as the knife cuts off the kernel. The measurement of wheat hardness by the Temnometer resulted in widely scattered data. In order to obtain a reliable representative value for a given lot of wheat, at least three-hundred kernels were required. The test results were greatly effected by moisture content.

To measure the compressive resistance, Mepplink (1968) constructed an apparatus, called the Comprimeter which is quite similar to the Temnometer. The Comprimeter measures the force required to compress a kernel between a flat-ended rod and plate. About 150 kernels were tested to obtain an average compressive resistance. Kernel size and grain moisture were found to effect the results of the Comprimeter test to a considerable extent. Khrushchev and Berkovich (Kuprits, 1967) designed an instrument, called the PMT-3, to measure the resistance to indention at different locations of an endosperm cross section. These were termed micro-hardness measurements. The arithmetic mean of the micro-hardness values, measured for the different locations, was used to represent the hardness of a variety.

The first automatic wheat hardness tester was developed by Cargill's grain research laboratory (Cargill, 1970). A sample of grain was ground against a wheel; the quantity worn off was measured and digitally computed, resulting in a hardness reading in forty-five seconds. The automatic unit receives and weighs the grain, sends it through the abrasive tester, computes the degree of hardness, and prints out the results.

Shelef and Mohsenin (1967) made use of the Instron testing machine to subject wheat grains to uniaxial compression loads. Under a constant rate of deformation of 0.020 inch/min., the load-deformation relation was linear up to a certain load, non-linear beyond it. Cyclical loading and unloading to a low constant load within the linear portion of the load-deformation curve showed that the deformation was partly recovered and partly residual. The residual deformations remained constant. Under these conditions, the behavior of the wheat grains was considered approximately Hookean, and the classic theory of elasticity was adapted for evaluation of their modulus of elasticity. The apparent value for the modulus of elasticity obtained for wheat at 9.1% moisture content ranged from 1.6×10^5 to 8.3×10^5 psi. The relations between stress or strain applied and modulus of elasticity possibly could be used as a hardness index. However, there is a rather large range in the apparent modulus of elasticity.

Katz et al. (1959) modified a commercial portable soft metal tester (known as the Barcol Impressor) to test grain. In this test, a pre-loaded stylus is forced into grain sections prepared by means of a micro-tome. The displacement of the stylus, measured by a dial micrometer, is used as a hardness index. This test does not produce reliable results and is very time-consuming as only about fifty kernels could be tester per day.

Bennett (1950) devised an electrically operated machine for the rapid determination of hardness of grain. A mechanical feeder delivers grain at a uniform rate between an inner driven wheel (at 33 RPM) and an outer wheel which rotates only when grain is being crushed. Since it is propelled by the pinning action of crushing grain. Indexes to hardness are obtained by a hydraulic piston-regulated recorder unit which is driven by the outer crusher wheel when it rotates. The hydraulic pressure in generated in a hydraulic cylinder, the plunger of which is actuated by the torque transmilled to the crusher frame by the crusher wheels. Either the number on the recorder or the hydraulic pressure, as registered on a pressure gauge, may be used as an index of hardness.

There are five basic ways to evaluate the hardness of wheat using a grinding or abrasive action:

1. Measure the total energy required to grind a sample
2. Measure the peak torque required to grind a sample
3. Measure the total time required to obtain 100% pearling or 100% grinding
4. Measure the percent pearled off or ground in a specific time period
5. Run a sieve and particle size analysis on the pearled or ground wheat sample.

Anderson, Pfeifer, and Peplinski (1966) applied the BHT and a pin mill to obtain hardness or friability indexes that clearly reflect differences in wheat types and varieties and that give some indication of the response to fractionation by fine-grinding and air-classification of the flours from the wheat. Their work pointed out that the work expended in grinding proved to be quite insensitive as a kernel hardness index. Their tests indicate that the wheat can be rated according to kernel hardness or friability, or both, by measurement of the flour yield or of the flour fraction surface area in a standardized grinding process. Tests are more sensitive when the flour fraction surface area is measured, and most sensitive when flour fraction surface area per unit of work is the hardness or friability criterion.

Williams (1967) did work on a particle size index (PSI) test. Its principle depends on the breakdown of wheat kernels under a standard grinding procedure and the test gives a constant measure of kernel hardness. Kernel hardness as measured by the PSI method has been shown to be closely related to damaged-starch content as measured by three chemical methods.

Chemical methods as used in this procedure are expensive and also time-consuming.

Pearling Index

The pearling test for the determination of kernel hardness of wheat was developed by Taylor, Bayles, and Fifield (1939). The machine used is the Strong-Scott barley pearler and consists of a carborundum wheel coupled to an electric motor; the wheel rotates in a closed case which provides an abrasive action to the charge of wheat. The kernels whirl around between the pearling stone and screen mantle, the motion of the kernels being due to the transversal grooves in the stone and circular motion of air currents within the case. The kernels bounce against the stone and the screen mantle; the abrasive action that occurs is due to the impact and the acquired relative velocity between the stone and wheat kernels. The wheat charge is treated (pearled) for a definite time period. The percentage of material retaining on the screen mantle is defined as the pearling index. It has been found that as the grain gets harder, less material is removed in pearling and the greater the pearling index.

Kramer and Albrecht (1948) did work studying the pearling test using the Strong-Scott barley pearler on small wheat samples. They made the following observations:

1. In soft wheat, the amount of wheat pearled off is inversely related to the moisture content of the wheat

when moisture is raised in dry samples.

2. There is a linear relationship between sample size and pearling index, irrespective of length of time pearled or of kernel hardness in the range studied.
3. The action of the pearler is such that an index of each kernel in a sample is obtained independently of the average index of the sample.
4. The relationship between pearling time and pearling index is not linear, although curvilinearity is not very pronounced in pearling time from thirty to sixty seconds.

In addition there was a distinct tendency for variability or standard error to increase as the charge was reduced and for coefficients of variation to decrease with longer periods of pearling. They also found that in mixtures of soft and hard wheat each component of the mixture retains its own pearling index, the index of the mixture being the weighted average according to proportions of mixture constituents. They reported no significant differences between pearling indexes from single and fractional pearlings. Here, fractional pearling refers to the pearling of each sample in successive time increments (twenty seconds increments up to three minutes); single pearling is performed in a single operation for the corresponding period of time. They adjusted the charge and the period of operation so that tests from a smaller sample could be compared with the standard one in case the quantity of wheat available was limited.

A method of adjusting the pearling indexes was proposed, and the procedure was discussed.

Work done by Taylor, Bayles, and Fifield (1939) with the Strong-Scott barley pearler indicated that there appears to be only a slight relationship, if any, between the percentage pearled off and the protein content for either the winter or spring varieties. More recently, Greenaway (1969) points out that wheat hardness is associated with a high-protein, vitreous wheat.

McCluggage (1943) did work on the effects of certain factors on the pearling test. He studied the effects of the temperature of the wheat and the pearler, sifting of the pearled wheat, speed of the stone and length of pearling time, size of charge, size of the screen used in pearler, and moisture content of the wheat. The results of McCluggage's work imply that the pearling test is not sensitive to wide ranges in temperature. Therefore, no elaborate system of temperature control is required to reproduce the same pearling results from day to day and the ordinary variations of room temperature should have very little effect upon the results obtained. The accuracy of the pearling test can be slightly increased by sifting the pearled wheat over a 20-wire sieve. There would appear to be no fundamental reason why different laboratories employing slightly different techniques regarding speed and pearling time should not be able to obtain the same relative results. The size of the charge introduced into the pearler makes quite a difference in the amount pearled off. Therefore, the charge size used for any test must be specified. The size of the screen used in the pearler had little effect on the outcome. However, to avoid error, it is pointed out that worn screens and stones should be replaced from time to time. The study indicated that variances in the percentage pearled off is caused by the variety and the station at which the sample was grown and that the moisture content had very little effect in the 7% to 15% moisture range.

However, work done by Katz, Collins, and Cardwell (1961) disagree. They point out that the hardness of hard wheat varieties (hard red winter and durum) diminishes with increasing moisture content. Soft white winter wheat showed no significant change in hardness up to a moisture content of 13%. Above this value of moisture content, their hardness showed a rapid decrease. In all cases, the kernel to kernel variation in hardness was much greater at high moisture content than at low moisture content with durum wheat kernels giving the most uniform results and soft white kernels giving the least uniform results.

Mechanical and rheological properties of grains were studied by Zoerb and Hall (1960). They concluded that moisture content had the greatest overall influence on the strength properties of grain. The compressive strength modulus of elasticity, maximum compressive stress, and shear stress generally decreased in magnitude with an increase in moisture content. Energy requirement for impact shear was higher than static shear at a high moisture content but the modulus of resilience and modulus of toughness did not vary greatly.

Standard Pearling Test

McCluggage (1943) proposed the following standard technique for pearling test:

Equipment

1. Strong-Scott Barley pearler, equipped with a number 30 grit stone, a 10-mesh screen of wire 0.041 inch in diameter (Tyler code Tijor) and driven at a speed of 1725 RPM.
2. Stop watch or other timer of equivalent accuracy. (Interval timers of the current-interrupting type have been found unsuitable.)
3. Balance sensitive to 0.01 gram.
4. Sieve covered with number 20 wire.

Methods

1. Each charge (20gm) is weighed from cleaned, unsized wheat that has been throughly mixed.
2. The charge is placed in the machine with the stone running at full speed; sixty seconds later the slide outlet is opened; and ten seconds later the motor is stopped.
3. The pearled wheat is sifted over the 20-wire screen

to remove dust and powdered material. The weight of the material remaining on the screen is recorded as the weight of pearled wheat.

Results

1. Triplicate determinations should be made on each sample. These replicates should be averaged and the results expressed as the percentage of the origional sample removed in pearling (percentage pearled off).

Pearling Index Inadequacies

The Strong-Scott barley pearler has been the most popular device for measuring wheat hardness in the United States because of its simplicity and performance. However, the use of the barley pearler as a standard device does not seem practical with the original design for many reasons. The following inadequacies are known from the literature:

1. Its results vary greatly among laboratories.
2. The range of pearling indexes from the hardest to the softest wheat is relatively narrow due to the size factor of the kernels.
3. Pearling index data will not separate clearly the harder classes.
4. The machine was not designed to give data as consistent as possible.

Materials may remain on the screen mantle or between wires of the screen after operation. Also, the slot opener design is not adequate as a slight movement of the slot opener due to kernel impact may allow material to escape from the enclosure. It is surprising to note that no one attempted to improve the Strong-Scott barler pearler to overcome the disadvantages of the device for a period of years.

An attempt was made to improve the pearling technique by Chung (1971). His work resulted in a new method for determining the hardness of wheat by measuring the total energy required to pearl a charge of wheat for a specified time period. It was pointed out in this method, called the pearlograph technique, that the eighty second pearling energy had the highest correlation with energy parameters from the Brabender torque-time curve. The eighty second pearling energy could be assessed as one of the most desirable parameters investigated in that study. The pearlograph was obtained by the modified barley pearler so that the variation of the pearler shaft torque could be measured as the pearling proceeds. Based on statistical and physical considerations, the relation between the eighty second pearling energy and the maximum rupture resistance was proposed as a reference parameter for wheat hardness. This new parameter was termed as "the soft hardness number"; the scale ranges from zero to one hundred with linear subdivisions.

Chung (1971) pointed out several facts concerning the pearlograph chart:

1. The pearlograph chart height at any instant during the process indicates the material remaining within the pearler.
2. The best measure of wheat hardness can be obtained from the recorder chart area.
3. The kernel size effect is made very small by the compensating characteristics of the pearlograph curve for the different kernel size distributions.
4. The pearlograph chart area is affected by the variation of grain moisture in such a way that, as grain moisture is increased in the range of 7 to 15 percent, the pearlograph area for the hard wheat remains relatively constant.
5. The optimum pearling time, for which the pearlograph chart area is integrated and used for rating wheat hardness, was determined as an eighty second duration. The basis for the decision was the maximum ratio of the average effect of variety to that of grain moisture.

OBJECTIVES

The objectives of this study were: (1) to make an extensive survey of the literature regarding the existing techniques of determining the needed grain hardness measurement; (2) to modify and improve the Strong-Scott Barley Pearler in order to provide a more reliable and practical machine for wheat hardness tests; and (3) to conduct experiments to standardize the test procedures for wheat hardness tests with the modified Strong-Scott Barley Pearler.

MATERIALS AND EQUIPMENT

Experimental Material

The wheat used in this study ranged widely in variety, region, and history of growth. Seven varieties of wheat were chosen to represent the various hardness classes. Table 1 summarizes the wheat used in the study. The samples were obtained through the office of Markey Quality Research Division, ARS, USDA, Manhattan, Kansas.

The Barley Pearler

The barley pearler consists of three main units: driving, pearling, and particle collection. Pearling occurs between a rotating carborundum wheel and a stationary screen mantle with openings equivalent to a Number 10 Tyler sieve. The screen is surrounded by the main frame; a side wall provides a journal bearing to support one end of the wheel shaft. A chute is cast as a part of the opposite side wall of the frame for introduction of wheat samples into the pearler. This side wall is fastened to the main frame of the pearler by four cap screws and contains a journal bearing to provide support to the other end of the wheel shaft.

Wheat kernels whirl around between the screen and the rotation stone; the motion of kernels is due to transverse grooves in the stone, to impact (bouncing) with the stone, and to the

Table 1. The Wheat Tested in the Study

Wheat Class	Region of Growth	Variety	Year of Growth
HRW	Pullman, Washington	Bezosztaja	1970
SWW	Walla Walla, Washington	Omar (club)	1970
HWW	Farmington, Washington	Burt	1970
HRS	Sidney, Montana	Justin	1970
SRW	Wooster, Ohio	Reed	1969
Durum	Fargo, N.D.	Leeds	1970
Durum	Fargo, N.D.	Lakota	1970

circular air currents created. Most of the pearling is done when the kernels bounce from the screen mantle enclosure.

The wheel shaft is directly connected to an electric motor and runs at 1725 RPM. The bottom of the screen enclosure is equipped with a manually operated gate which is closed during pearling and opened after pearling to remove the pearled particles remaining on the screen mantle.

The particles which passed through the screen mantle are collected within a large container and the pearled particles remaining on the screen are collected within a smaller container when the sample slot is opened. The general view of the pearler is shown in Figure 1.

Modification of the Barley Pearler

The barley pearler was modified to provide a more desirable and reliable system for measuring wheat hardness. Chung (1971) modified the pearler to allow installation of a torque measuring device with the modified system being termed the pearlograph. The original pearler from the manufacturer was utilized and was further modified to attempt to improve the reliability of the machine. Figures 2 and 3 show the original and modified machines.

For the torque measuring device, the drive motor was replaced by a double-ended shaft motor with the same operating speed. Ball bearings were mounted on the motor shaft and fastened to stands. A longer base was constructed to accommodate the extended length necessary to support the stands. For convenience of operation, the pearler timer was mounted to the side of the extended base. The pearler and motor shafts were connected, in line, by a jaw-type flexible connector. Torque transmission to the pearler was measured by utilizing the dynameter principle. A coupling arm was extended from the frame of the drive motor. A cantilever beam, as shown in Figures 4 and 5, was used to restrain the reaction force resulting from the torque of the cradled motor. A ball bearing was mounted to the end of the coupling arm to allow concentrated contact on the restraining beam with a small frictional effect. Two strain gages were mounted at the center of the restraining beam, one on the upper surface and another on the lower. To improve

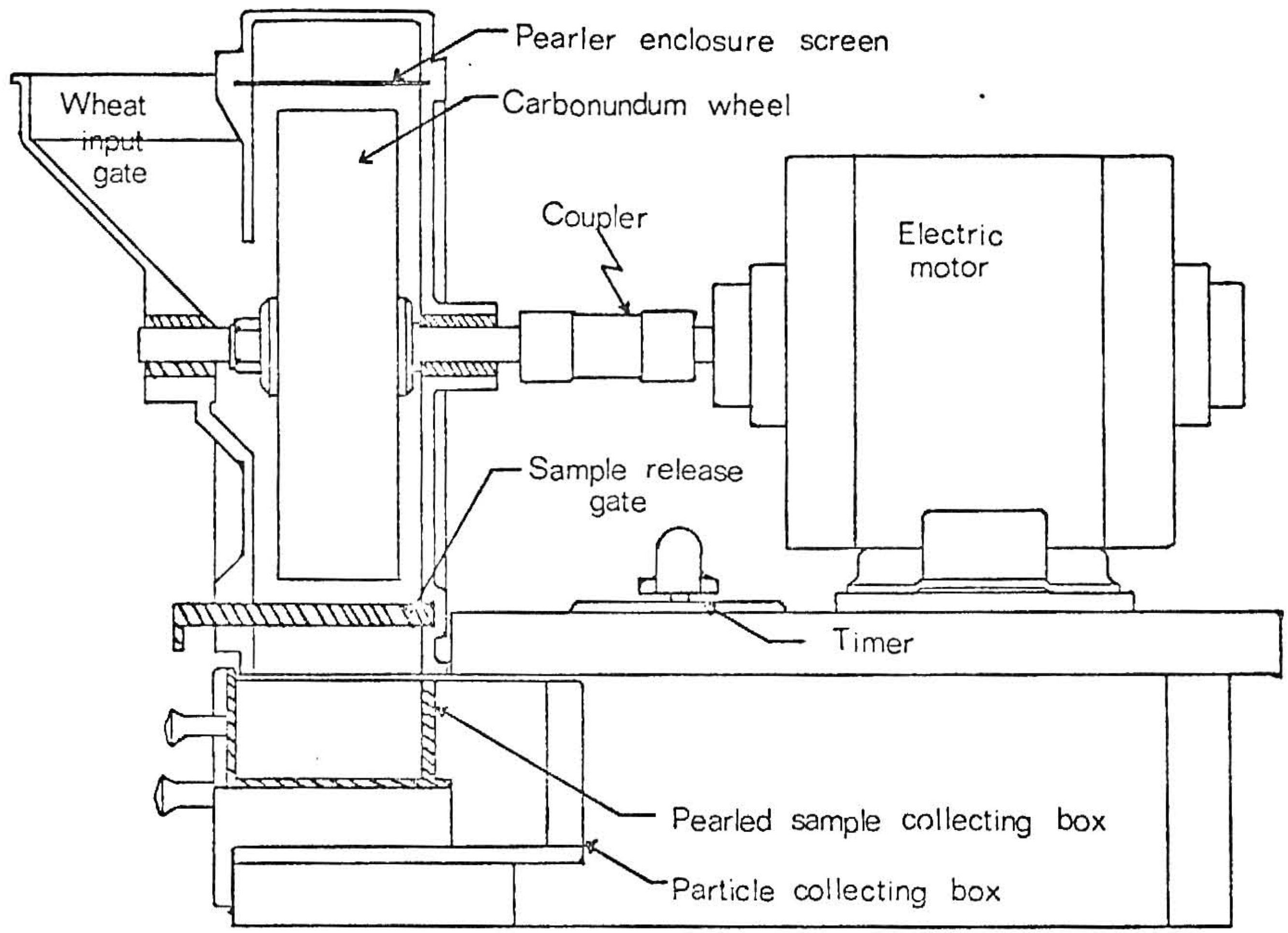

Figure 1. General View of Strong-Scott Barley Pearler.

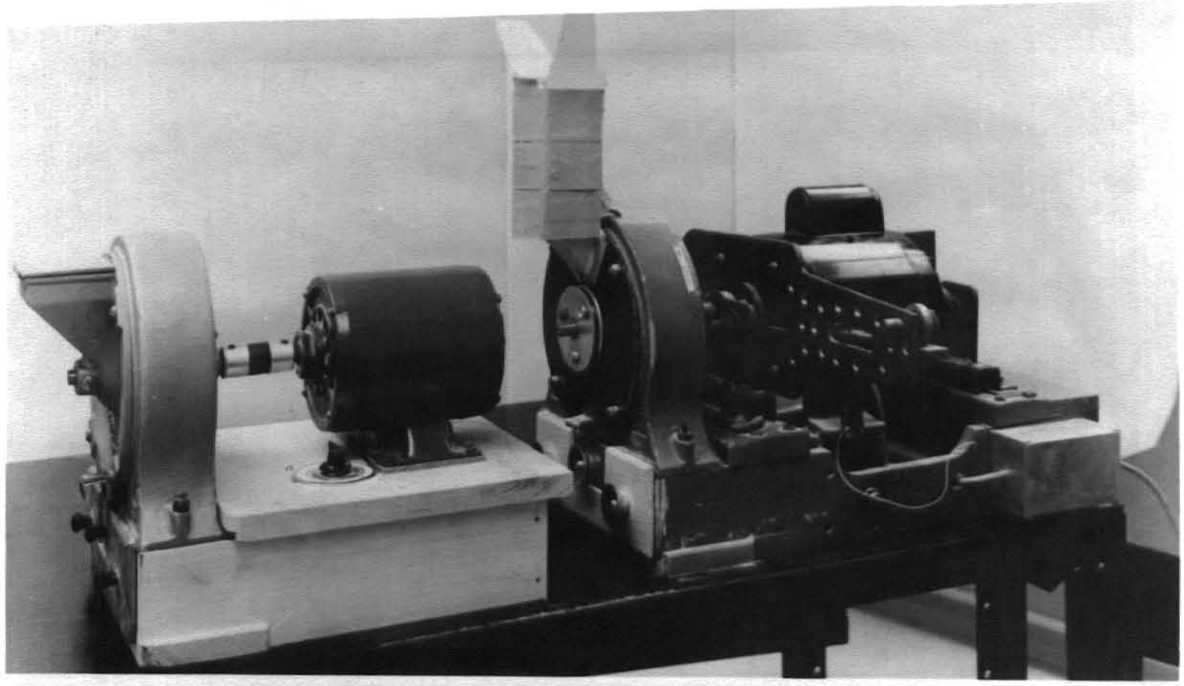

Figure 2. The Barley Pearler Before Modification (left) and After Modification (right), Front View.

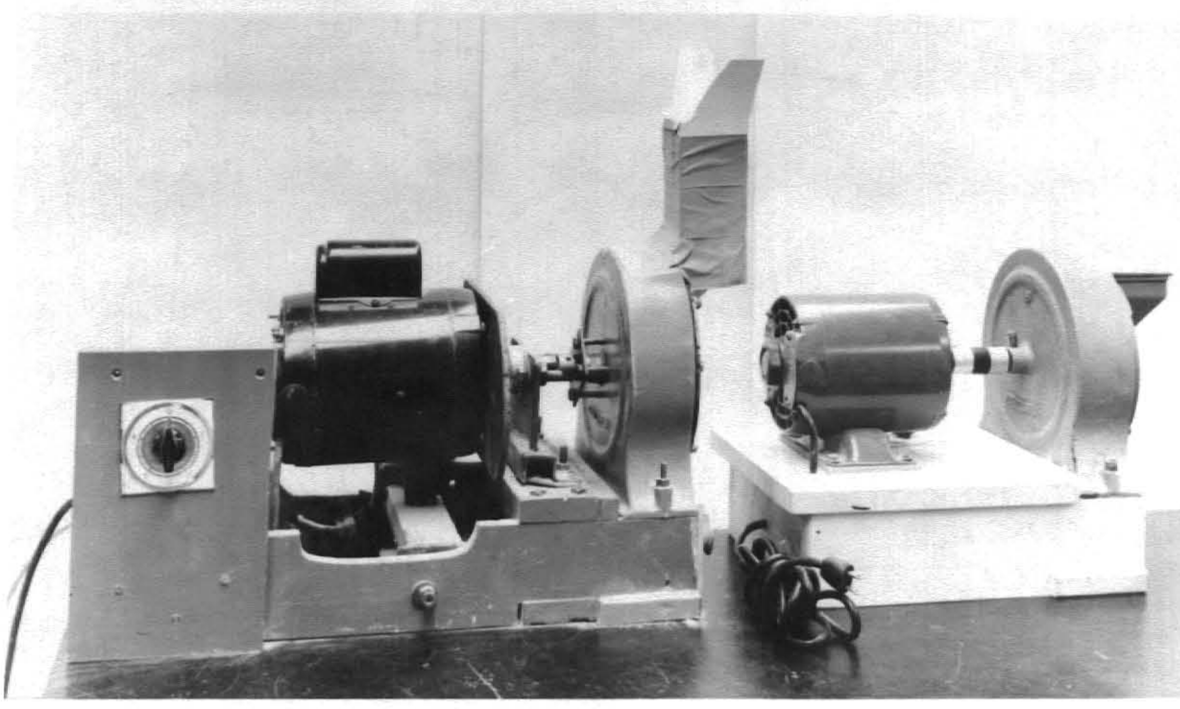

Figure 3. The Barley Pearler Before Modification (right) and After Modification (left), Rear View.

bridge sensitivity and bridge null-balance, two more identical gages were later mounted adjacent to the gages of the first set. The physical and electrical arrangements of the four active gages are shown in Figure 6.

The system was further modified by replacing the journal bearings with ball bearings. With the original system, it was noted that the wheel shaft was allowed to move in a lateral direction. This lateral movement of the wheel shaft causes an error in results obtained from the system. Also a period of time was needed to allow stabilization of the system due to friction temperature increases in the journal bearings of the original pearler. This time was the period during which the temperature rise would equalize in both the shaft and bronze bearing. The amount of temperature rise could also be affected by dust particles working into the contact area causing more error in results. By using small ball bearings in place of the journal bearings, equalization time was made very small due to the large decrease in friction. The bearings selected for use in this modification (Fafnir AW8AK) contained very good dust seals so as to eliminate the dust problem. Also, lubrication in the ball bearing was much more even. The lateral shaft movement was eliminated without an increase in friction due to the fact that the bearings used can withstand small thrust loads. The coefficient of friction for this type application of these bearings is around 0.001 (Anderson and Zaretsky, 1970).

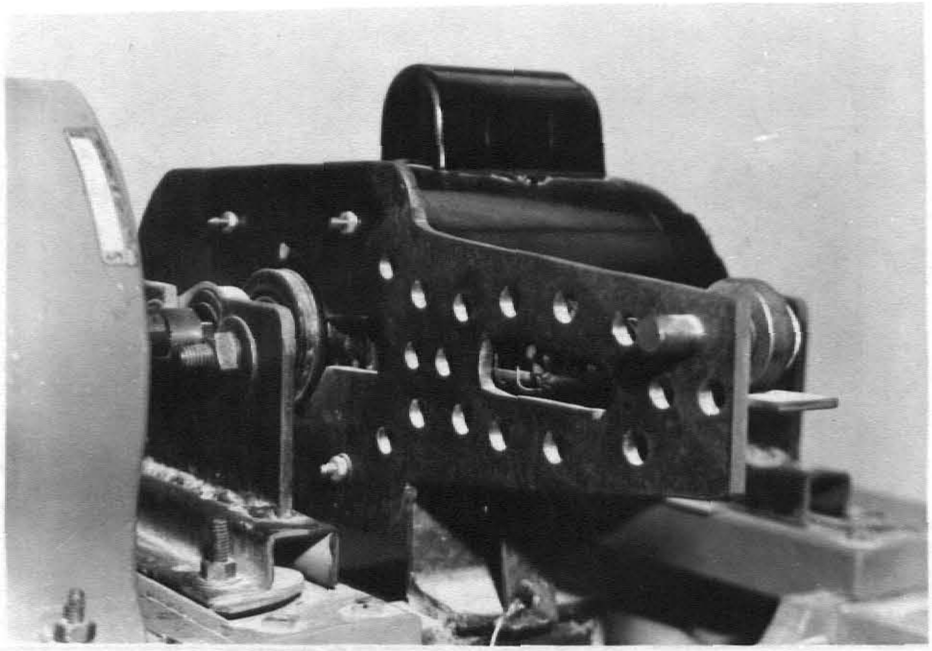

Figure 4. Coupling Arm Utilizing the Dynameter Principle.

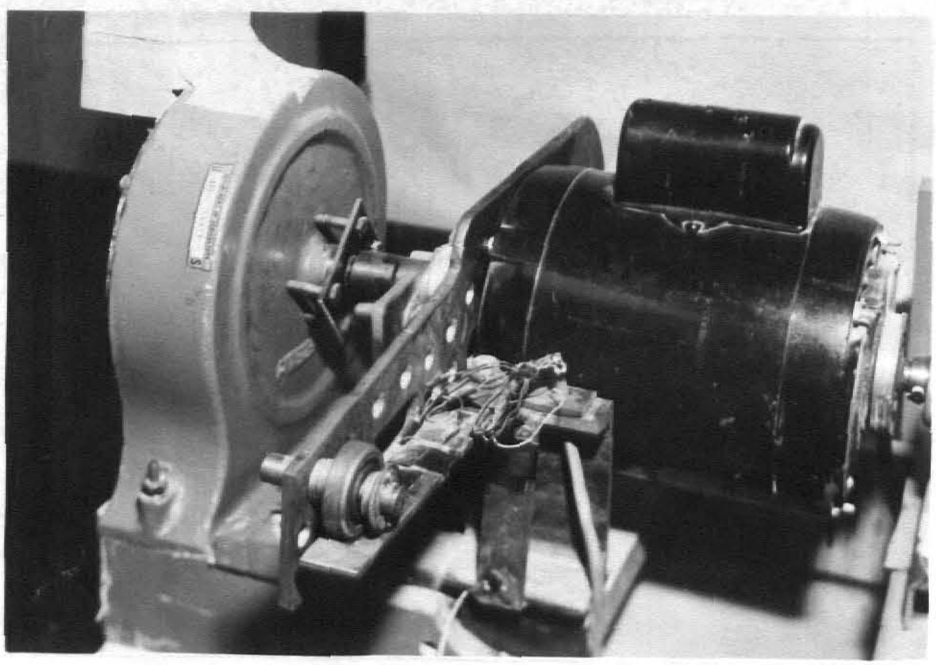

Figure 5. Cantilever Beam with Strain Gages Used to Measure Pearler Torque.

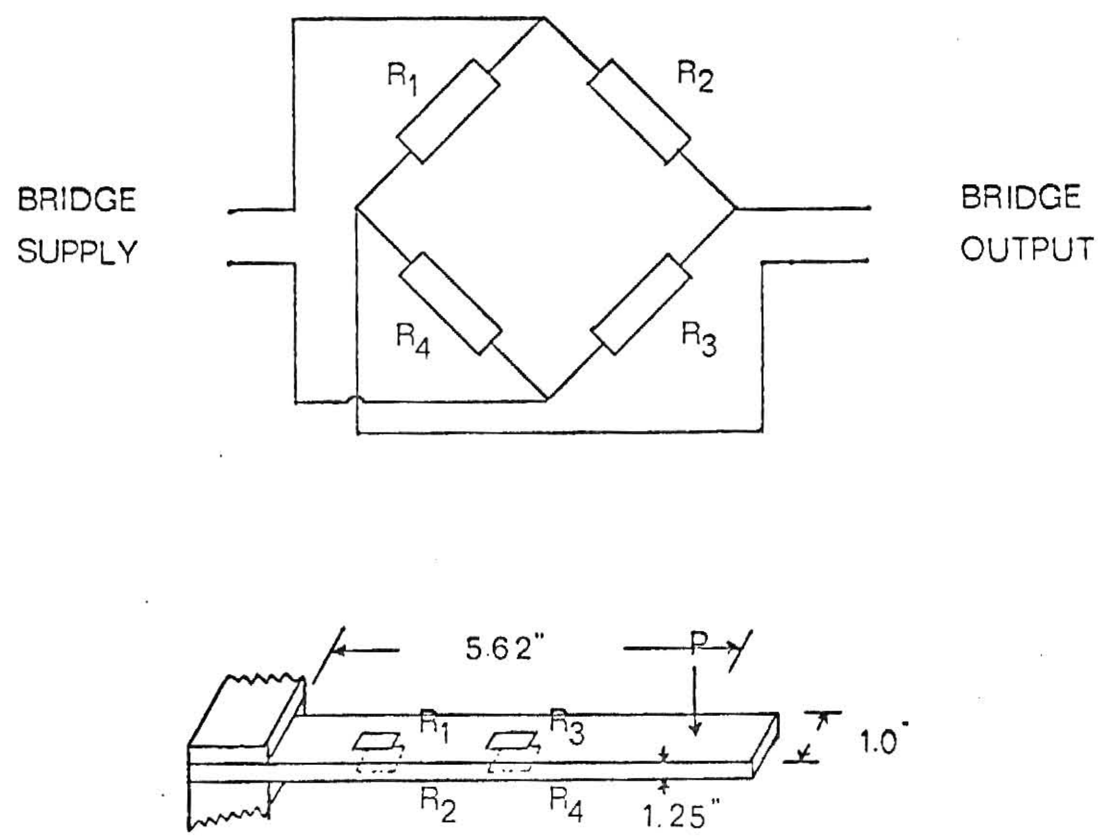

Figure 6. Strain Gage Location and Wiring Diagram Used for Sensing Torque.

The vibration resulting from the pearler operation also decreased with bearing use.

Another problem noted with the original pearler design was the pearler sample release gate. The vibration of the pearling action caused the gate to open partially allowing material to escape from the screen mantle enclosure. The original gate was so shaped that it is difficult to be constructed. The modified pearler contained a pearler release gate which was shaped as a rectangle so as to allow easy construction. In addition the modified gate allows the installation of a nylon scraper on the top of the gate. This scraper would remove all powdered and granular material from the top of the gate and force it into the pearled sample when the gate is opened. This nylon scraper is also tight enough so as not to allow vibration to open the gate, thereby preventing the escape of any material from the pearling action. A view of the original and modified gate designs is shown in Figure 7.

The chute used for introduction of samples into the pearler was modified so that a lid would not have to be used to keep particles from escaping out the chute during operation. This was accomplished by inserting baffles at opposing angles inside of the chute. Any material bouncing inside the chute would strike one of the baffles and return to the machine to undergo the pearling process. A view of the sample chute is shown in Figure 8.

To further improve the pearler, an even sample-fed system was used to standardize the introduction of samples into the pearler. The even-feed system used consisted of a Syntron Vibra-Flow Feeder. This system is vibrating mechanism which causes the wheat kernels to flow evenly down a tray and into the pearler. The even-feed system is shown in Figure 9.

Energy Recording Systems

Strain gages used for sensing torque output from the hardness measuring machines were connected to a strain gage amplifier-indicator. The system used in this study was the Daytronic Model 300 D transducer amplifier-indicator. The electronic signal from the Daytronic system was fed into a recorder, the Beckman Model 100500, which utilizes a standard 10-inch cartesian coordinate recording chart. The recorder was equipped with an integrator unit, the Disc Model 236 Chart Integrator. An overall view of the Daytronic amplifier-indicator and Beckman recorder systems is shown in Figure 10. Figure 11 shows a typical example of the pearlograph curve with some of the terminology used.

Another method of measuring energy was to use a wattmeter to monitor the performance of the electric motor which is actually a monitor of energy input to the pearler. For this purpose an Esterline-Angus Graphic Wattmeter was used. To determine the power-factor, p.f., of the electric motor, a General Electric Recording Ammeter and a Simpson Model 263 Voltmeter were used.

Figure 7. Pearled Sample Release Gates.

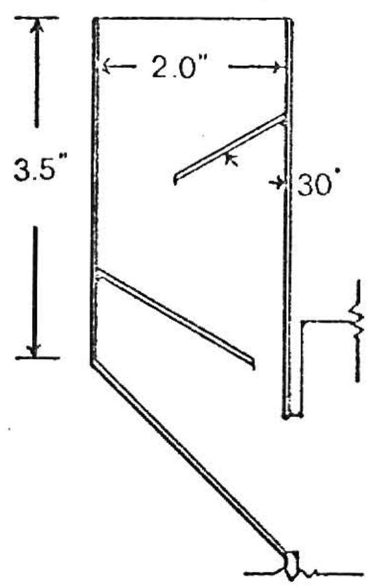

Figure 8. Sample Input Gate Used on Modified Pearler.

Figure 9. Syntron Vibra-Flow Feeder.

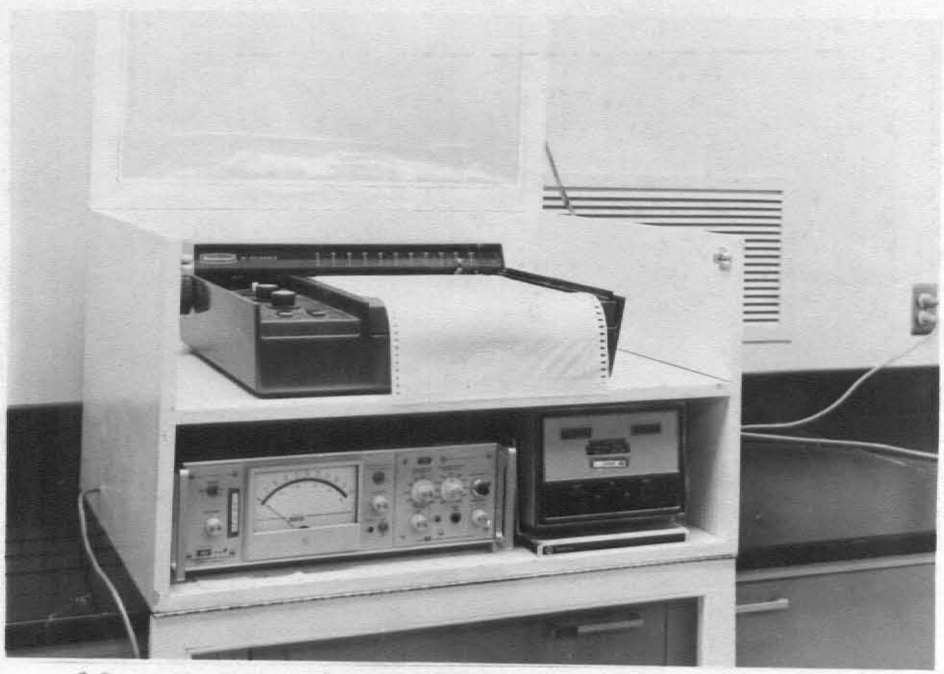

Figure 10. Daytronic Amplifier-Indicator and Beckman Recorder System.

The equation needed to determine p.f. is:

$$\text{p.f.} = \frac{\text{watts}}{(\text{volts})\ (\text{amps})} \tag{3}$$

Having the power factor, the watts input can be converted to an energy or torque value. A view of the electric monitoring instruments are shown in Figure 12.

Calibration

To convert the chart values produced by the pearlograph, calibration points were established throughout the working range of torques. Input torques were obtained by placing different known weights on the loading arm.

The chart height corresponds to the instantaneous torque, which can be obtained by multiplying the length of the loading arm by the weight loaded. Instantaneous power can be obtained by multiplying the torque by the angular speed, w, of the rotating shaft:

$$\text{Power} = \text{Torque} \times W \tag{4}$$

Constant speed was used throughout the experiments. The energy required for pearling can be obtained by integrating the power with respect to the operating time:

$$\text{Energy} = \int_0^{\theta} \text{Power}\ d\theta \tag{5}$$

This corresponds to the area under the curve on the output chart. For convenience, the recording chart speed was set at five inches

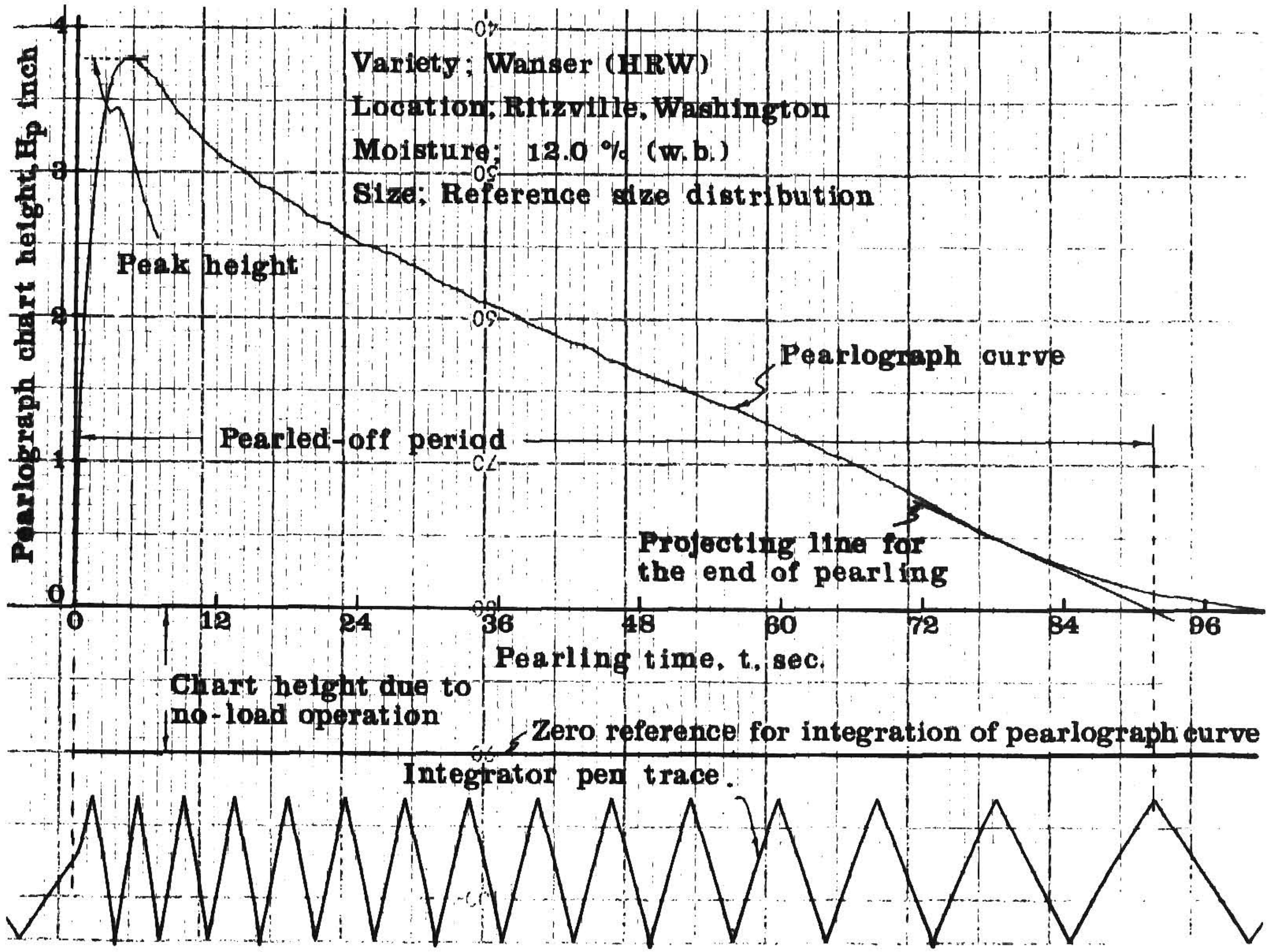

Figure 11. Typical Pearlograph Curve and Intergrator Pen Trace.

per minute for all tests.

The relationship between the pearler torque and chart height is given by:

$$T_p = 0.0084 \text{ h.} \quad (6)$$

where

T_p = pearler torque in Kg-m.

h = chart height in inches.

Energy consumed for pearling was calibrated against the area of the pearlograph chart by the equations given above. The indicated value recorded by the integrating unit was a constant multiple of 1.4 times the actual area in the chart. The calibrated energy is given by:

$$E_p = C_p \; 0.13006 \quad (7)$$

where

E_p = calibrated energy in Kg-m.

C_p = integrator count in pearlograph chart.

The wattmeter is a direct measure of power input. The power factor was determined by a curve as shown in Figure 13. This was obtained by loading the motor and obtaining measurements of watts, volts, and amps. The actual power then may be obtained by multiplying the watts times its corresponding power-factor value obtained from the curve. For convenience in this study, the direct watt meter readings were used in the analysis of data. The pearling energy may be obtained by the relation:

$$Epw = AAW\ 5479.5 \text{ watt-sec.} \tag{8}$$

where

Epw = Energy from wattmeter in watt-sec.

AAW = Area under wattmeter curve in inches squared.

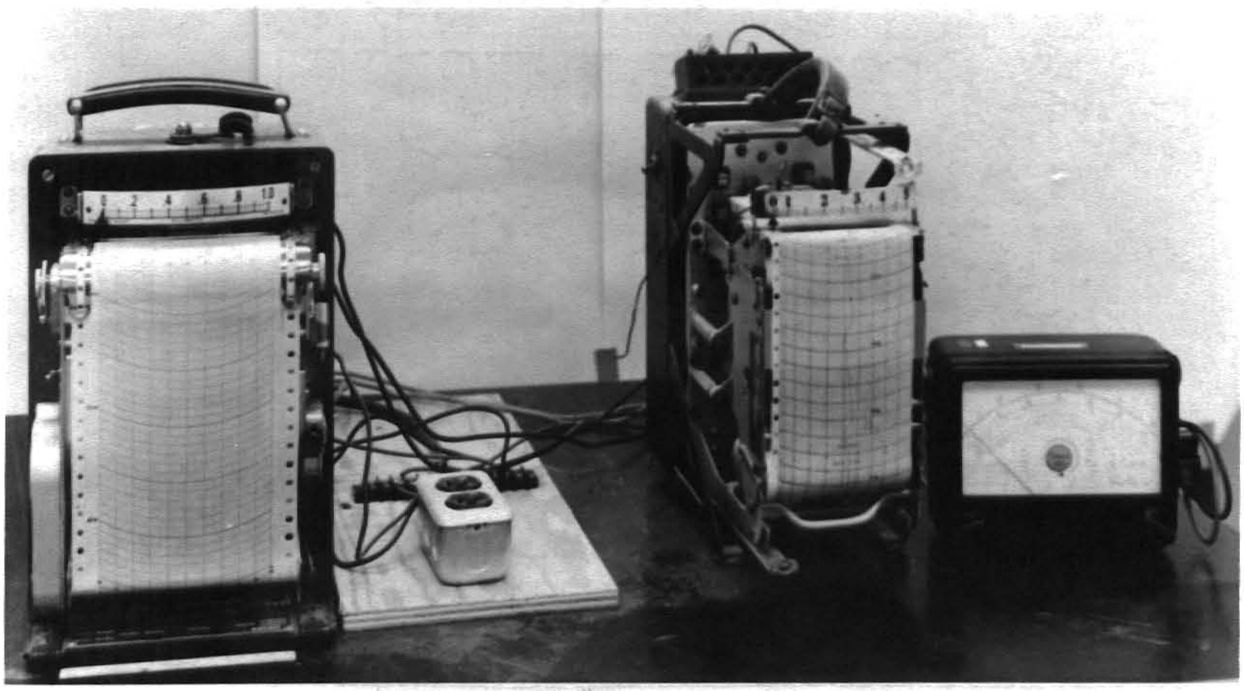

Figure 12. Electronic Monitoring Instruments.

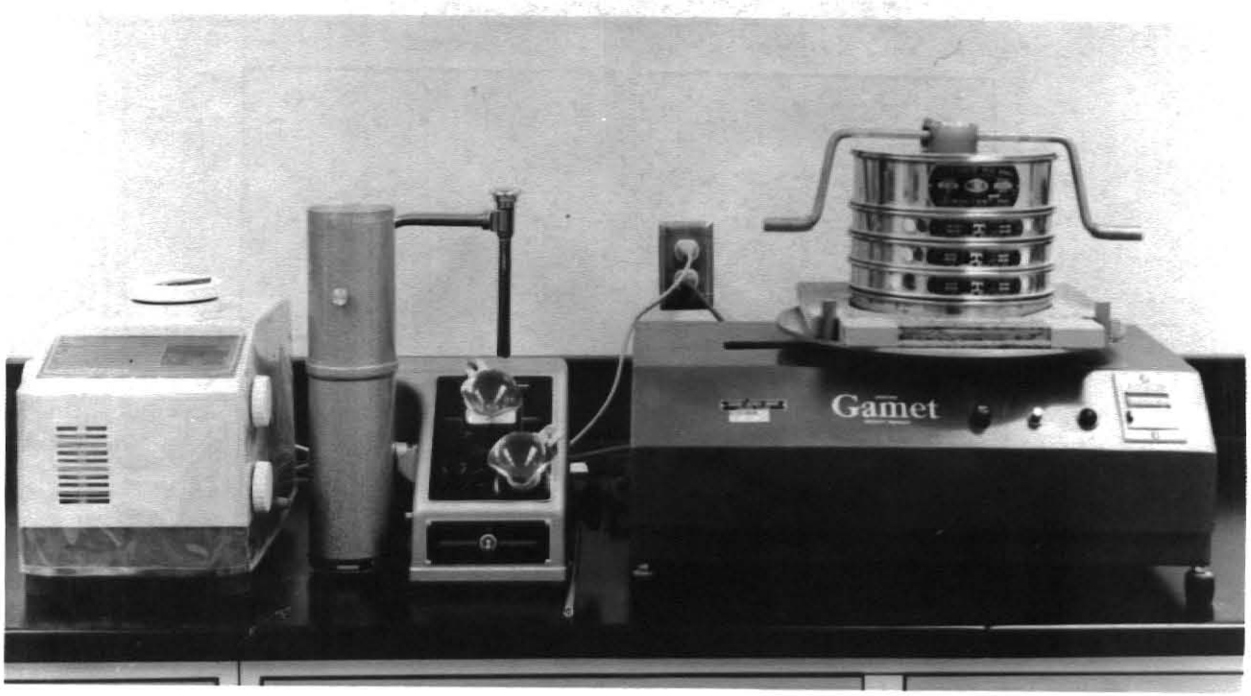

Figure 14. Gamet Shaker.

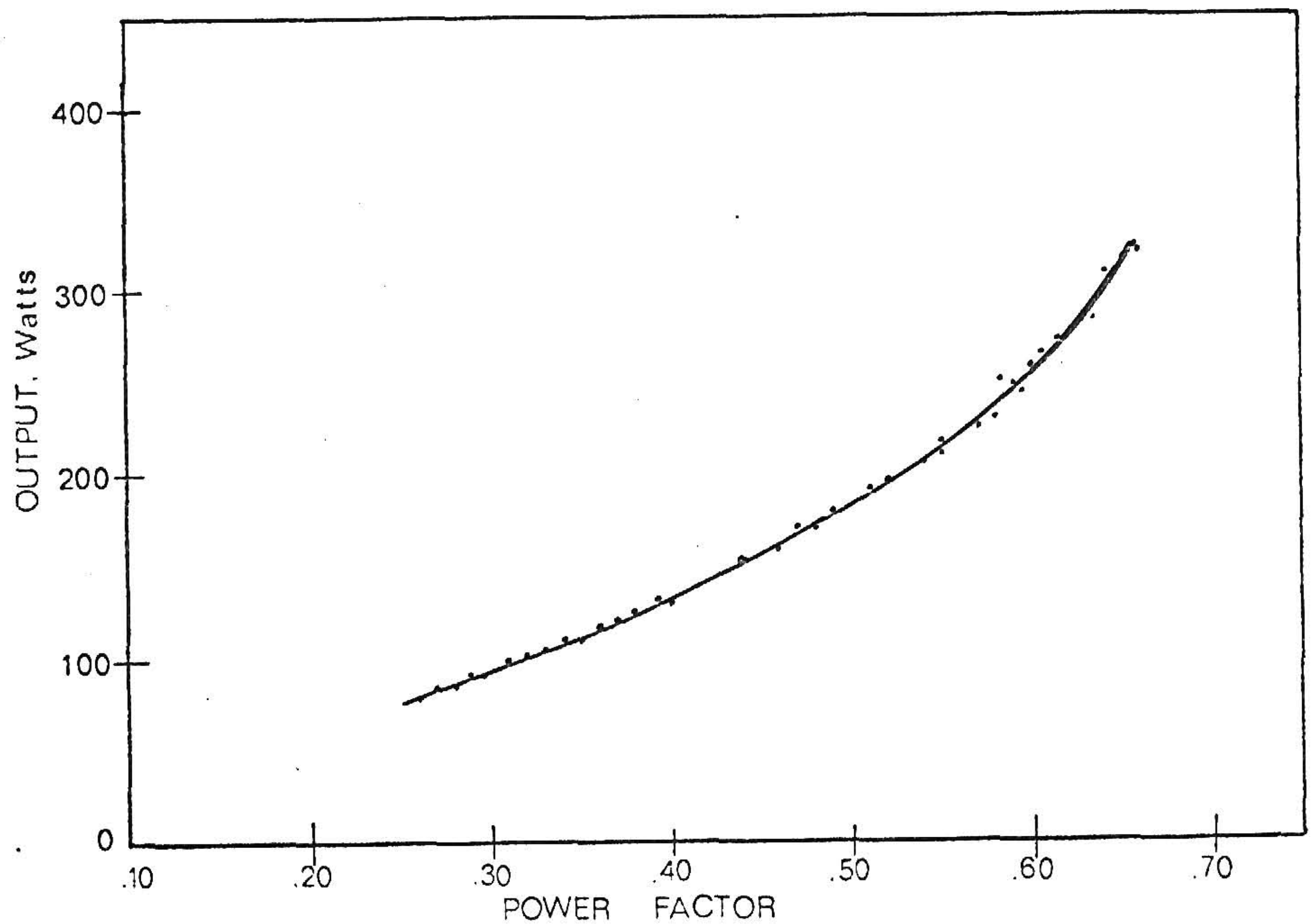

Figure 13. Wattmeter Calibration Curve.

EXPERIMENTAL PROCEDURE

Material Preparation

About three hundred grams of a wheat sample was obtained from a bulk sample within the shipment bag. The bulk samples contained fines, broken kernels, and foreign material. To attempt to insure that the initial samples for each test were nearly uniform, the fines and some foreign materials were screened out by using a Tyler Number 10 sieve and about one minute of hand shaking. Each of the three hundred gram samples was then tempered to the proper moisture level. The method of tempering used was to add the necessary amount of water (by pouring directly into the grain and mixing well) to bring the sample into the desired moisture level and allowing to stand for ninety six hours in a closed container. The moisture content of the sample was then determined by the oven method. Each sample was tested at approximately 9%, 12% and 15% moisture content.

Testing Procedure

To get an adequate torque response, it was determined that a sample charge of about forty-gram was needed. All of the tests were conducted using forty-gram samples. After checking to see that all of the recorders were properly zeroed and were running, the forty-gram sample was introduced into the running pearler for a period of eighty seconds. (Work done by Chung (1971) indicated that 80 seconds pearling produced the optimum pearlograph response). The sample release gate was opened after eighty seconds of pearling and the sides of the pearler was tapped lightly to dislodge any materials remaining in the pearler. The pearled sample collected in the small container was placed in a Tyler Number 10 sieve and was shook briefly to remove dust in the sample. The pearled sample was then weighed and recorded. This weight expressed as a percent of the original sample weight is the pearling index. The ground material collected in the larger container was then placed on a set of Tyler sieves, numbers 10, 14, 20 and Pan, and run for one hundred cycles on the Gamet shaker shown in Figure 14. After shaking for one hundred cycles, the weight of the individual screens with ground material on them was recorded. Each of the recorder strip charts was then labled with a code which corresponded with a master sheet. The master sheet indicated the date, variety of wheat, classification of wheat variety, moisture content, and test number. All weights were accurate to ±0.01 gram. All tests were repeated five times. Figure 15 shows the pearlograph system used in this study.

Experimental Design

Twenty-one series of tests were conducted with each series consisting of five replications for studying the effects of two factors with the modified barley pearler, moisture content of the sample and variety or classification of the sample. Seven different varieties of wheat, having moisture contents of approximately 9%, 12% and 15%, were tested. Factors and their levels examined are summarized in Table 2.

Table 2. Factors and Their Levels Examined

Variety	Classification	Moisture* Content
Bezosztaja	HRW	9% 12% 15%
Omar	SWW	9% 12% 15%
Burt	HWW	9% 12% 15%
Justin	HRS	9% 12% 15%
Reed	SRW	9% 12% 15%
Leeds	Durum	9% 12% 15%
Lakota	Durum	9% 12% 15%

*Approximate Values

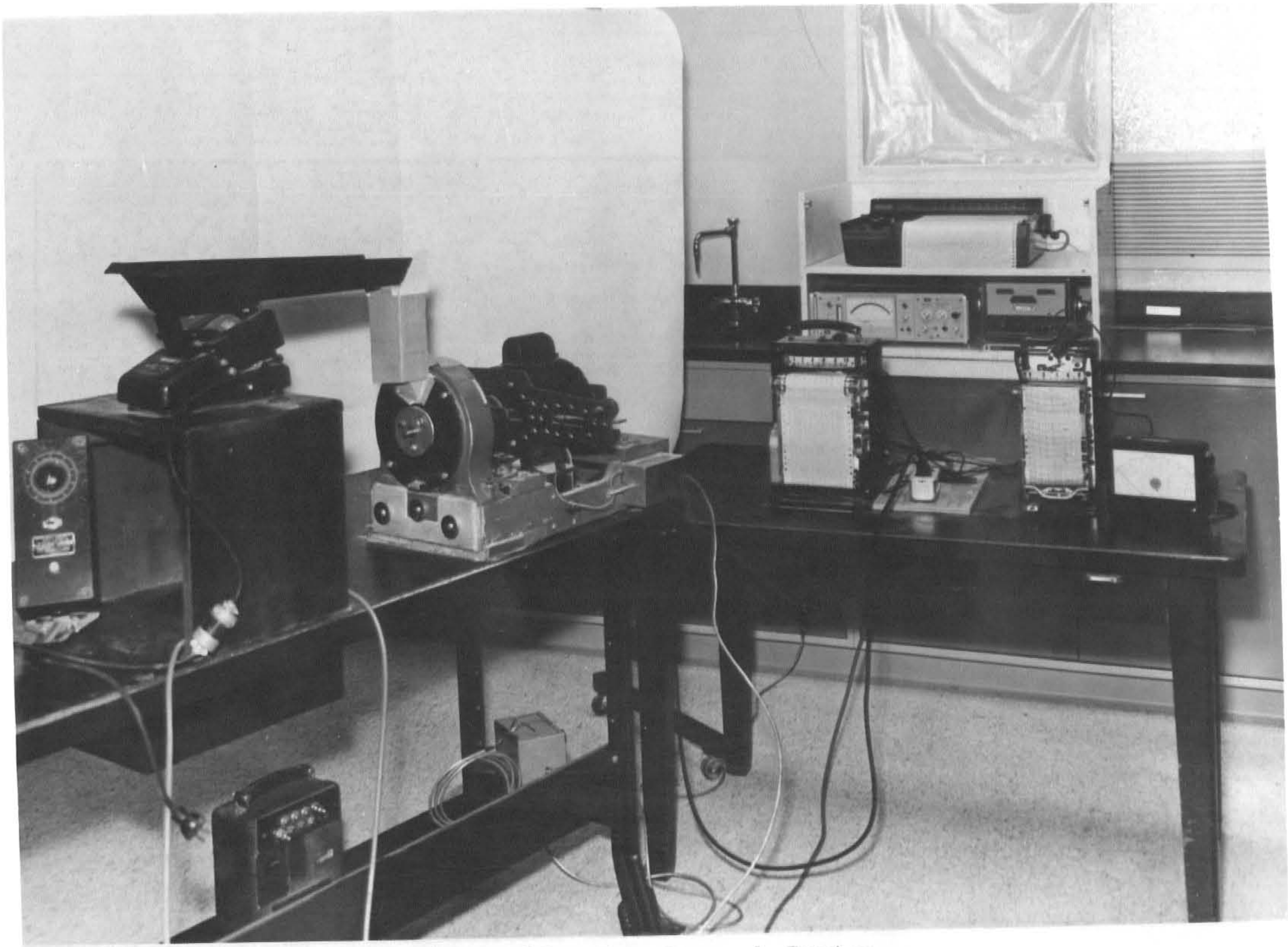

Figure 15. Pearlograph System.

Eight different measurements were made to examine the above factors in a statistical analysis. These eight measurements were: weight on Tyler Number 10 sieve; weight on Tyler Number 14 sieve; weight on Tyler Number 20 sieve; weight on Pan sieve; peak pearlograph torque; peak wattmeter value (watts); area under pearlograph curve (energy in Kg-m); and area under wattmeter curve (energy in Watt-sec). Also measured for comparison in the statistical analysis was the pearling index which is the industry standard used with the Strong-Scott Barley Pearler.

The physical properties of the wheat samples were determined by commercial cereal grain laboratories. The properties used in this study were: bulk density; true density; 1000 kernel weight; protein content; and milling yield. These values will be compared to the above nine measurements. It should be noted that milling yield tests are not done on Durum wheat. The computations on the data will take this into account.

RESULTS AND DISCUSSION

Experimental Results

A complete summary of data taken in this study is found in appendix A. The physical properties of protein content, PCT, and milling yield, MYD, were determined by commercial laboratories and are expressed in percent. The moisture content was determined by the oven method in the laboratory and is expressed in percent. The bulk density, BDN, true density, TDN, and 1000 kernel weight, KWT, were determined according to cereal grain methods. The nine hardness indicators consist of: the industry standard, the particle size reduction parameters, and the energy parameters. The industry standard is the pearling index, PLI, which is expressed as a percent. The particle size reduction parameters, cummulative oversizes for Tyler sieve numbers 10, 14, 20 and pan (S10, S14, S20, and PAN respectively) are the weight of fines remaining on the screens after 100 cycles in the Gamet shaker expressed in grams. The energy parameters include: the peak torque, PTQ, expressed in inches of pearlograph chart height; pearlograph area, AAP, expressed as the integrator count (which can be converted to Kg-m by equation (7)); peak watts, PWT, expressed as inches of wattmeter chart height; and wattmeter area, AAW, expressed as wattmeter area in square inches (which can be converted to watt-seconds by equation (8)). A summary of parameters is given in table 3.

Table 3. A summary of the Parameters Involved

Parameter	Definition	Method	Unit
PCT	Protein Content-protein analysis	Commercial lab	%
MYD	Milling Yield-flour yield analysis	Commercial lab	%
BDN	Bulk Density	Cereal grain method	lbs/bu.
TDN	True Density	Cereal grain method	gms/cm^3
KWT	1000 Kernel Weight	Cereal grain method	grams
PLI	Pearling Index material remaining in enclosure at end of pearling period.	Strong-Scott Barley Pearler	%
S10	Weight of fines material from pearler remaining on #10 Tyler sieve.	Particle Size Reduction	grams
S14	Weight of fines material from pearler remaining on #14 Tyler sieve.	Particle Size Reduction	grams
S20	Weight of fines material from pearler remaining on #14 Tyler Sieve.	Particle Size Reduction	grams
PAN	Weight of fines material from pearler collected in pan sieve.	Particle Size Reduction	grams
PTQ	Peak torque-peak on the pearlograph time curve	Energy	Kg - m
AAP	Pearlograph area-total energy from area under pearlograph curve.	Energy	Kg - m/sec

Table 3. Continued

Parameter	Definition	Method	Unit
PWT	Peak Watts-peak reading from wattmeter time curve.	Energy	watts
AAW	Wattmeter Area-total electrical energy from area under wattmeter curve.	Energy	wat-sec

Statistical Model

The statistical model assumed for this research was that of two fixed variables and one interaction term. That is:

$$X_{ijk} = \mu + V_i + M_j + (VM)_{ij} + E_{ijk} \qquad (9)$$

where

X = hardness index

μ = grand average of all possible X_{ijk}

V = variety variable effect

M = moisture variable effect

VM= moisture and variety interaction

E = errors in system and procedures

Assuming this model, the following statistical computations were performed on the data: the analysis of variance, Duncan's Multiple Range Test; coefficient of variation; and correlation coefficients. These statistical tests were used to analyze the test results as to their ability for indicating variety hardness, hardness differentiability and their relationships to each other.

Variety Hardness

One of the objects of this research stated earlier was to improve the Strong-Scott Barley Pearler so that it would have the ability to separate the wheat hardness levels with little or no moisture effect. By analyzing the data taken from the pearler in an analysis of variance table, one can use the F test (or variance ratio) to point out the effect of each variable. A very large F ratio tells us that the difference between groups is more than can be accounted for by sampling error. A small F ratio then tells us that a larger portion of the difference between groups can be accounted for by sampling error. Then for a hardness indicator that has good hardness-level separating ability at any moisture level, one must look for a relatively high F ratio for the hardness-variable (variety) and a low F ratio for the moisture variable. A summary of the F ratios for each hardness indicator is shown in Table 4.

Table 4. The Results of Analysis of Variance for Various Hardness Indicators

Hardness Indicator	F Ratio		
	Variety	Moisture	Interaction
S10	304.805	312.297	51.896
S14	369.182	569.061	98.628
S20	150.867	128.313	34.559
PAN	68.914	38.181	2.928
PTQ	413.567	27.366	20.665
PWT	266.758	168.247	12.460
AAP	119.163	23.375	9.888
AAW	20.537	59.882	3.101
PLI	1220.683	1743.200	69.762

F-value at $\alpha = 0.05$

In looking at the table summarizing the F-test values, one can readily see that the pearling index (PLI) offers by far the highest F ratio for separating hardness levels of wheat. However the pearling index also has the highest F ratio for the moisture effect. Then for any sample tested by the pearling index method, the moisture content of the sample will most likely effect the hardness level (value). The interaction F ratio for this indicator is fairly high adding more support to the idea that the moisture content will effect the pearling index outcome. Of the four sieve sizes tested, the Pan seemed to show the best results. The pan had a variety F ratio of about twice that of the moisture ratio. Also, the interaction term proved to be insignificant. The other three sieve sizes tested all had large moisture effects and a large amount of interaction between moisture and variety indicated by a relatively large interaction F ratios. The pearler peak torque (PTQ) and the pearlograph area (AAP) both show some promise of hardness indicators. Both have fairly high variety F ratios and low moisture F ratios. The interaction F ratios are also fairly low. The pearler peak torque seems to show a stronger variety effect indication than does the pearlograph area measurement. The remaining two variables, peak wattmeter reading (PWT) and wattmeter area (AAW), contain higher moisture effect F ratios and lower variety ratios.

It should be pointed out that in only two cases the interaction F ratio proved to be insignificant. The two cases were for the wattmeter area and for the pan sieve variables. Of these two, only the pan sieve produces the type of measurement needed, mainly a large variety effect and a low moisture effect. The results point to the fact that the variety effect measured is almost twice the moisture effect measured when the pan sieve indicator is used. This is part of a time-consuming sieve analysis which is a disadvantage and is not desired for large scale use. Of all the variables tested, the pearling index, the pearlograph area and the peak pearling torque are the variables which are applicable to a direct hardness level reading machine. However, the pearling index also picks up a large moisture effect. For the desired results, it seems from the analysis of variance table that a peak pearlograph torque or pearlograph area indication of hardness level would produce the best results.

Hardness Differentiability

In order to detect hardness differences easily, it is desirable for a hardness indicator to have its range as large as possible. One of the desirable features of hardness measuring techniques as stated by Mepplink (1968), is differentiability of hardness between soft and hard wheats.

Coefficient of Variation

The coefficient of variation is a measure of the degree of variation of data to the mean value of the data. Hardness indicators used in this study were evaluated as to their differentiability by computing the coefficients of variation. A summary of the computation results is given in Table 5. A higher coefficient of variation indicates a larger degree of variation from the mean value and, indirectly, a better hardness differentiability. Of the particle size reduction indicators, the Number 14 sieve shows the greatest differentiability. In the energy group, the pearlograph peak torque and the pearlograph area show the highest, but both are far below the Number 14 sieve. The 1000 kernel weight shows the greatest differentiability, among the physical properties. The pearling index has the best differentiability of any of the indicators other than the particle size reduction group.

To find the effect of moisture content on differentiability, the coefficient of variation was computed at each moisture level. A summary of the computation results at the 9% moisture level is given in Table 6. At this moisture content level, it was found that the Number 14 sieve provided the best differentiability with the pearling index showing best when excluding the particle size reduction indicators. Of the energy indicators, pearlograph area and peak torque were best while 1000 kernel weight was best among the physical properties. Table 7 gives a summary of the computation results at the 12% moisture level. It was found that the Number 14 sieve (a particle size reduction indicator) provided the best differentiability but that the physical property, 1000 kernel weight, provided the best of the remaining indicator groups. The pearlograph torque

Table 5. Coefficients of Variations Used to Compare the Differentiability of Wheat Hardness

Indicator	Mean	Standard Deviation	Coefficient of Variation (%)
S10	0.898	0.648	72.147
S14	0.648	0.626	96.678
S20	0.398	0.290	72.732
PAN	11.829	2.801	23.680
PTQ	5.436	0.557	10.249
PWT	147.981	10.644	7.193
AAP	3553.333	325.864	9.171
AAW	1.957	0.127	6.499
PLI	61.793	11.097	17.958
BDN	60.628	2.597	4.284
TDN	1.350	0.034	2.506
KWT	33.174	5.571	16.795
PCT	11.514	1.624	14.105
MYD	63.740	2.866	4.295

Table 6. Coefficients of Variations Used to Compare the Differentiability of Wheat Hardness at 9% Moisture Content

Indicator	Mean	Standard Deviation	Coefficient of Variation (%)
S10	1.290	0.858	66.508
S14	1.075	0.861	80.088
S20	0.558	0.384	68.845
PAN	13.078	2.242	17.145
PTQ	5.458	0.588	10.773
PWT	147.428	8.392	5.692
AAP	3502.828	350.460	10.005
AAW	1.925	0.091	4.726
PLI	53.571	11.506	21.479
BDN	60.628	2.623	4.326
TDN	1.350	0.034	2.530
KWT	33.174	5.626	16.959
PCT	11.514	1.640	14.243
MYD	66.740	2.906	4.354

was best among the energy indicators with the pearling index showing a slightly higher coefficient of variation than the energy indicators. A summary of the computation results at the 15% moisture level is given in Table 8. At this moisture level, the Number 10 and Number 14 show about the same amount of differentiability. The peak wattmeter indicator shows the best differentiability among the energy indicators. The 1000 kernel weight is best among the physical properties.

One can note that even though the Number 14 sieve shows the best differentiability, it also has the greatest moisture effect (values range from 80.088 to 44.684). The values shown for pearling index also decreases rapidly as the moisture content increased. The pearlograph area decreased also, but at a slower rate with values ranging from 10.005 to 7.067. The physical properties remained fairly constant. This is due to the laboratory procedures (standardized procedures) used in the milling analysis laboratory. These factors therefore cannot be considered as to moisture effects in this study. Considering the relationships above, the pearlograph area used for differentiability would be more desirable as it shows less of a moisture effect and is approximately constant in the 9% to 12% moisture content range. The pearlograph peak torque could be used, however its relationship to moisture content is more complex with both positive and negative regression characteristics. If the pearling index or the Number 14 sieve are to be used as

Table 7. Coefficients of Variations Used to Compare the Differentiability of Wheat Hardness at 12% Moisture Content

Indicator	Mean	Standard Deviation	Coefficient of Variation (%)
S10	.790	.467	59.058
S14	.516	.372	72.067
S20	.333	.232	69.743
PAN	11.745	2.795	23.794
PTQ	5.333	.627	11.754
PWT	153.343	8.980	5.857
AAP	3502.857	345.746	9.870
AAW	2.057	.110	5.344
PLI	63.989	9.582	14.974
BDN	60.628	2.622	4.326
TDN	1.350	.034	2.530
KWT	33.174	5.626	16.959
PCT	11.514	1.640	14.243
MYD	66.740	2.906	4.354

Table 8. Coefficients of Variations Used to Compare the Differentiability of Wheat Hardness at 15% Moisture Content

Indicator	Mean	Standard Deviation	Coefficient of Variation (%)
S10	.613	.275	44.913
S14	.352	.159	44.684
S20	.304	.126	41.212
PAN	10.664	2.856	26.777
PTQ	5.517	.439	7.954
PWT	143.171	11.905	8.315
AAP	3654.314	258.266	7.067
AAW	1.888	.133	6.001
PLI	67.818	6.366	9.386
BDN	60.628	2.623	4.326
TDN	1.350	.034	2.530
KWT	33.174	5.626	16.960
PCT	11.514	1.640	14.243
MYD	66.740	2.906	4.354

differentiability indicators, the moisture content must be standardized to produce accurate results.

Duncan's Multiple Range Test

In this portion of the data analysis, all the averages were computed for the statistical model given in equation 9. The variety (V_i) averages were computed by taking the sum of all observations at all moisture levels of each variety divided by the total number of observations for each measuring system being evaluated. The moisture (M_j) averages were the sum of all observations of all varieties at each moisture level divided by the total number of observations for each measuring system being evaluated. These two sets of averages are the only ones of concern in this study. These averages were then listed in order with the highest number first and Duncan's multiple range test was performed. A table summarizing the results of the test is shown in Table 9. This table shows the listing of averages from highest to lowest and the insignificant differences groupings.

The discussion of the Duncan's multiple range test will be divided into two parts. First will be the discussion of the outcome due to moisture effects and second will be the discussion of the variety effects as measured by each of the hardness level indicators.

Table 9. Groupings of the Duncan's Multiple Range Test

Variate	Hardness Level Indicator								
	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI
	9%	9%	9%	9%	15%	12%	15%	12%	15%
Moisture	12%	12%	12%	12%	9%	9%	12%	9%	12%
	15%	15%	15%	15%	12%	15%	9%	15%	9%
	HWW	HWW	HWW	SRW	HRW	HRW*	HRW	HRW	Lakota
	SWW*	SRW	SRW *	SWW*	HRS	SRW*	HRS*	HRS *	Leeds*
	SRW*	Leeds*	Leeds*	HRS*	SRW	HRS	HWW*	SRW *	HRW *
Variety	Leeds	SWW *	SWW *	HWW *	HWW	Leeds*	Lakota*	Lakota*	HRS
	Lakota	Lakota	Lakota*	HRW *	Leeds *	HWW *	Leeds *	Leeds *	HWW
	HRS	HRS	HRW *	Leeds *	Lakota*	Lakota	SRW *	HWW*	SWW
	HRW	HRW	HRS *	Lakota*	SWW	SWW	SWW *	SWW*	SRW

*Indicates Insignificant Difference at $\alpha = 0.05$

<u>Moisture Effect</u>. All of the sieve sizes used in the sieve analysis (S10, S14, S20 and Pan) were ranked the same. In other words, the average weight collected on the individual sieves over the seven-variety range was always more at the lowest moisture level (9%) than at the highest or medium moisture levels (12% and 15%). In every case, the 12% moisture level produced a screen weight that was less than the 9% moisture level and more than the 15% moisture level.

The pearling index ranked the moistures in the inverse order as would be expected due to the relationship between the amount remaining on the screen and the amount of kernel surface removed by the pearling process. The higher weight remaining on the screen would classify a harder wheat as more energy would be required to obtain 100% pearling. Then, a softer wheat would require less total energy for pearling. After a set period of time, less soft wheat would remain on the screen mantle than would remain in the case of a harder wheat. From the above relationships and relating to moisture contents, it may be concluded that moisture content tends to affect the pearling action to the effect that the lower moisture content tends to produce more pearling action. More of the individual kernel's surface will be removed with a lower moisture content than will be removed with a high moisture content. This result agrees with work done earlier by Kramer and Albrecht (1948) and others. Then for any standardized procedure for testing hardness of wheat, using this method, the moisture content must be specified and held constant for all samples to be tested.

The area under the pearlograph curve which is a total energy measurement also supports the above statement. Pearlograph area also rated the moisture levels the same as the pearling index. However, statistical analysis points out that pearlograph area clearly forms only two distinct groups as far as total energy is concerned. The highest moisture level (15%) tested requires the highest amount of energy for pearling. The 9% and 12% moisture levels do not cause enough difference in energy requirements to clearly separate the two moisture levels. Therefore, one may conclude that the total pearling energy measurement system is affected to a lesser degree by differing levels of moisture content in the 9% to 15% range.

The peak pearlograph torque once again pointed out that more energy is needed for pearling at the 15% level of moisture. However, the torque measurement determines that the intermediate moisture level (12%) requires the least amount of torque. This may be an indication that the ideal moisture level for testing hardness is 12%.

The peak wattmeter reading and area under the wattmeter curve both point out that the least amount of electrical input power is required with the highest moisture level (15%). They also show that the most input power is required with the intermediate moisture level (12%). This might be an indication that the 12% moisture level is the critical moisture level when using energy or peak input power measurements.

Variety Effect. In rating the varieties according to hardness, the outcome of some of the various methods is not clear cut. The pearling index seems to be a good indicator of hardness. The pearling index results pointed out a clear classification of hardness in almost every case. Lakota Durum wheat was classified as the hardest variety which seems reasonable. Statistics point out that there is no significant differences in hardness between the Leeds Durum and Hard Red Winter classes. The drawback to this outcome is that the pearling index may not be able to separate the two classes. It should be pointed out that two varieties of durum wheat were tested. The outcome may be reflecting a difference in the two Durum varieties such as protein content. In all the remaining varieties, there is a clear distinction between classes or varieties with Soft Red Winter wheat being the softest class.

The wattmeter area appears to be of little value as a hardness indicator. This is pointed out by the statistical lumping of all hardness classes into only three groups. The only class that this method was able to isolate was the Hard Red Winter. Wattmeter area then would be of little value used alone as it would only be able to classify Hard Red Winter wheat from a group of samples.

The pearlograph area again only isolated one class of wheat. Hard Red Winter Wheat was classified as the hardest with the remaining varieties grouped. Both of the Durum varieties were grouped together so this method may be useful in specifically classifying Hard Red Winter and Durum varieties and generally classifying the remaining varieties into hardness ranges.

The peak wattmeter reading does not appear to be of any value from this analysis. According to the statistical analysis, this method classified Hard Red Winter and Soft Red Winter wheats as being of the same general hardness which is clearly incorrect.

The pearlograph peak torque points out one interesting thing. It was the only method tested that separated each general classification of wheat and lumped both Durum varieties into one class. However, even though the classes were separated, the order of hardness is incorrect with any method that has previously been used.

The sieve analysis does not appear to point out any good hardness indicator as far as the size of sieve is concerned. The pan shows the closest agreement with the outcome of the pearling index. However, it divides the seven varieties into four groups thereby lumping two classifications into each group. The Number 10 Tyler sieve was the best of the four sieve sizes tested as it divided the seven varieties into six groups. However, the ranking of hardness does not seem to follow the same logical pattern as the pearling index which is the basis of many of todays' laboratory tests.

There were two hardness indicators that were affected by different moisture levels to a lesser degree. These were the pearlograph area and the Number 20 Tyler sieve. The pearlograph peak torque seems to be the best from the standpoint of variety separation, with the Number 10 Tyler sieve showing the second best. As the pearlograph peak torque can be obtained directly from the pearlograph area, the best overall hardness indicator with respect to differentiability is the pearlograph area.

Relationships Between Indicators

Nine different indicators were used to determine the hardness of wheat. These were the number 10 sieve, number 14 sieve, number 20 sieve, pan sieve, peak torque, peak watts, pearlograph area, wattmeter area and pearling index. These nine can be broken into two groups, particle size measurements and energy measuring systems. The pearling index is presently the standard use in industry with respect to the Strong-Scott Barley Pearler. However, Chung (1971) proposed a new standard, the soft-hardness number, based on the pearlograph area. Five physical properties of the sample were also determined. These were bulk density, true density, 1000 kernel weight, protein content, and milling yield. To determine the relationships between indicators, a linear correlation analysis was run on all of the above indicators. The data forms a symmetric matrix which measures the relationship, or more accurately the association, between indicators.

It is of interest in this study to determine the relationships between each of the nine hardness indicators and between the hardness indicators and five physical properties. The sieve analysis indicators clearly are a measure of particle size reduction relationships, while the remaining hardness indicators, with the exception of the pearling index, are a measure of energy requirements of the system needed for size reduction. The pearling index is related more closely to the fragmentation of solids theory.

From the correlation analysis which is summarized in Table 10, it can be seen that the indicators in the sieve analysis all have fairly high correlations. An interesting fact to note is that the screen sieves all correlate to a very high degree (above 0.90 correlation coefficient) but the pan sieve only has a small degree of correlation (below 0.32) with the three sized screens. All factors are significant at the 0.05 significance level. However, the pan sieve is significant at the 0.01 significance level only with the number 14 sieve. This suggests that more screen sieves need to be added to the sieve analysis between the number 20 sieve and the pan sieve. Adding more sizes would give a greater indication of the presence of particles that are

Table 10. Correlation Coefficients for All Hardness Indicators at All Three Moisture Levels.*

Variable														
S10	1.000													
S14	.953	1.000												
S20	.928	.942	1.000											
PAN	.234	.316	.239	1.000										
PTQ	-.323	-.212	-.152	.223	1.000									
PWT	-.282	-.133	-.167	.428	.673	1.000								
AAP	-.469	-.410	-.301	-.387	.697	.279	1.000							
AAW	-.352	-.254	-.303	.054	.327	.741	.366	1.000						
PLI	-.641	-.697	-.602	-.825	-.052	-.238	.531	.134	1.000					
BDN	-.314	-.258	-.166	-.607	.326	.120	.773	.329	.611	1.000				
TDN	-.289	-.288	-.203	-.662	.048	-.222	.610	.118	.661	.830	1.000			
KWT	-.349	-.218	-.167	-.005	.799	.720	.674	.505	.120	.628	.172	1.000		
PCT	-.268	-.232	-.256	-.197	-.144	-.126	.011	.001	.292	.001	.248	-.223	1.000	
MYD	-.129	-.056	-.012	.052	.755	.711	.407	.426	.013	.326	.221	.821	-.147	1.000
	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI	BDN	TDN	KWT	PCT	MYD

* $\alpha = 0.05$ $r = \pm 0.197$

$\alpha = 0.01$ $r = \pm 0.254$

smaller than the number 20 sieve. This in itself would probably lead to a high degree of correlation between all factors of the particle size analysis which would indicate that all of the size indicators are measuring the same physical quality, namely size reduction by grinding action.

Referring again to Table 10, it can be noted that peak torque, peak watts, pearlograph area and wattmeter area all have significance at the 0.01 significance level. This is to be expected as all are a measure of the total energy input into the system. Also apparent was the fact that peak torque and pearlograph area correlated to a high degree as did peak watts and wattmeter area. This was expected as the pearlograph area is the total energy which is a function of the instantaneous torque and the pearling time. And, the wattmeter area is again total energy and is a function of the instantaneous watts and pearling time.

Comparing the two energy measuring systems, it can be noted that the correlation is not as high as expected (0.366 correlation coefficient between wattmeter area and pearlograph area), even though it is significant at the 0.01 level. Both measurements are total energy measurements. This level indicates that the two systems measure the same general properties, namely energy, but not to the same degree. By comparing the two to the pearling index which is the standard for the industry, it can be noted that the pearlograph area shows a correlation coefficient of 0.531 (significant at the 0.01 significance level) while the wattmeter area only has a correlation coefficient of 0.134 (not significant at the 0.01 or 0.05 levels). As both are measuring the same physical properties, this would seem to indicate that the pearlograph area is the more desirable energy measurement system. Another factor that could cause this difference in correlations could be the accuracy (more correctly, the degree of error) of the measurement system components. The pearlograph area technique uses highly accurate strain gages, low distortion amplifiers and recorders which should lead to a low error factor in the final values. The wattmeter area uses a system of meters that monitors the electric energy input into the system. The meters themselves cause an error because the energy must pass through the meters resulting in an error induced by the meter. The use of meters with higher input impedance factors (higher ohms/volt ratios) would cause less of a circuit loading effect on the system to be measured and less induced error. By using better meters, the two energy measuring systems could possibly have higher correlations between each other and the pearling index.

It should be noted that peak torque and peak watts had a high correlation (0.673) indicating that they did measure the same physical properties. However, neither correlated well with the pearling index (0.238 for peak watts and -0.052 for peak torque) which indicated that they are measuring physical properties different than the pearling index. The two instantaneous energy measurements did correlate with the total energy measurement systems as expected.

Comparing the particle size reduction indicators and the energy indicators, one finds that the pearlograph area correlates well (significant at the 0.01 level) with all of the particle size indicators but in a negative direction. As the particles pass through the screen mantle, they no longer require energy accounting for the negative or inverse relationship. The wattmeter area also correlates with the number 10 sieve, number 14 sieve and number 20 sieve (significant at the 0.01 level) in the negative direction but did not correlate with the pan sieve. The peak torque and peak watts did not show a definite pattern as to their relationship with the particle size. The number 10 sieve had significant correlations ranging from -0.282 with peak torque, peak watts, pearlograph area, and wattmeter area. This fact points out that the number 10 sieve might be the best particle size reduction measurement with respect to the energy required.

As mentioned, the pearling index is the standard used with respect to the Strong-Scott Barley Pearler in industry today. The pearling index is the amount of the original sample charge remaining on the screen mantle of the pearler at the end of the pearling period expressed as a percent. In comparing the pearling index with the particle size reduction indicators, one finds a high negative correlation among all size indicators with the highest being with the pan sieve. One expects a high correlation here as the pearling index itself is a particle size reduction measurement determined by the weight of the particles which are larger than the number 10 sieve mantle in the pearler. In comparing the energy measurement indicators to the pearling index, we find that only the pearlograph area correlates (0.531 correlation and is significant at the 0.01 level). It appears that the pearling index could be used as a relative indication of the bulk density (0.611 correlation) and the true density (0.661 correlation) of a sample of wheat. Even though a significant level of correlation is shown between the pearling index and protein content (0.292 and significant at the 0.01 level), the correlation is not high enough to suggest that the pearling index could predict the protein content of a sample to any degree of accuracy. The pearling index did not correlate with the remaining physical properties.

Among the physical properties of the samples, it is interesting to note that the 1000 kernel weight seems to be the best indicator of physical properties. The 1000 kernel weight shows high correlation with the bulk density and the milling yield (both significant at the 0.01 level) and a moderate correlation with protein content (significant at the 0.05 level). But it showed no correlation with the true density.

In comparing the physical properties with all of the nine hardness indicators, we find that none of the hardness indicators correlated with all of the physical properties. Of the particle size reduction indicators, the number 10 sieve seems to be the best indicator of physical properties. The number 10 sieve correlated (at the 0.01 significance level with values from -0.269 to -.349) with all physical properties except milling yield. Of the energy measuring indicators, the pearlograph area seems to be the best indicator of physical properties. The pearlograph area correlated (at the 0.01 significance level with values from 0.407 to 0.773) with all physical properties except protein content.

Upon looking at the entire correlation coefficient matrix shown in Table 10, one can see that the number 10 sieve correlates at the 0.01 significance level with all of the remaining thirteen indicators except the pan sieve (significant at the 0.05 significance level) and the milling yield. This could indicate that the number 10 sieve is the best particle size reduction hardness indicator. Of the energy measuring indicators, we find that the pearlograph area correlates at the 0.01 significance level with all of the remaining thirteen indicators except protein content. None of the physical properties show any pattern of correlation with the other indicators.

An interesting fact to note is that the pearlograph area has one of the highest correlations with each of the physical properties of bulk density, true density, and 1000 kernel weight. The highest correlation coefficient with protein content was shown by the pearling index. The highest correlation coefficient with milling yield was shown by the 1000 kernel weight. This indicates that the pearlograph area could be used to predict the physical properties of bulk density, true density and 1000 kernel weight but could not directly be used to measure protein content or milling yield. The high correlation between milling yield and 1000 kernel weight indicates that indirectly the pearlograph could be used to indicate a measure of milling yield.

Thus far in this discussion, two independent variables have been considered along with their interaction and error terms. This was expressed as the mathmatical statistical model. in Equation 9. Certain conclusions have been drawn from an analysis of correlation on all data collected. As this study is concerned with a method of measuring true hardness, a further study of the data with the moisture level held constant would be of value. The data was separated into the three moisture levels (9%, 12% and 15%) and an analysis of correlation was performed on each level. Discussion of the results of this analysis will be divided into three groups: 9% level, 12% level and 15% level. All of the groups contain nine hardness indicators and five measures of physical properties.

<u>9% Level</u>: 9% level includes the data collected from tests run on seven varieties of wheat all at approximately 9% moisture content. A summary of the results of an analysis of correlation is shown in Table 11. Three of the particle size indicators (number 10 sieve, number 14 sieve, and number 20 sieve) correlated to a very high degree; however, the pan sieve did not correlate at a 0.01 significance level. This would indicate that the fines (smaller than a number 20 sieve) contain many sizes and that more sieves of a small size should be added. Addition of more sieves should cause a higher degree of correlation to occur among all of the particle size indicators. Of the energy indicators, it can be seen that all of the energy indicators correlate with each other at the 0.01 significance level with the exception of the pearlograph area versus peak watts which is significant only at the 0.05 level. Not one of the particle size reduction indicators correlates to a significant degree with all of the energy indicators. Of the energy indicators only the pearlograph area correlated with all of the particle size reduction indicators. The physical properties showed very little change in correlation values between each other at this moisture level or the overall correlations. The pearling index correlates very high with the particle size indicators and also correlated high with the pearlograph area. The index failed to correlate to a significant level with the remaining energy indicators. The pearling index correlated

Table 11. Correlation Coefficients for All Hardness Indicators at a 9% Moisture Level.*

Variable	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI	BDN	TDN	KWT	PCT	MYD
S10	1.000													
S14	.978	1.000												
S20	.959	.966	1.000											
PAN	.321	.354	.367	1.000										
PTQ	-.253	-.259	-.145	-.074	1.000									
PWT	-.232	-.210	-.136	.353	.756	1.000								
AAP	-.477	-.486	-.400	-.563	.786	.341	1.000							
AAW	-.357	-.332	-.333	.067	.442	.062	.452	1.000						
PLI	-.725	-.745	-.719	-.818	.163	-.207	.659	.109	1.000					
BDN	-.464	-.454	-.415	-.827	.438	-.031	.862	.238	.847	1.000				
TDN	-.477	-.462	-.439	-.768	.150	-.326	.645	.101	.819	.830	1.000			
KWT	-.359	-.353	-.277	-.290	.863	.664	.808	.453	.372	.628	.172	1.000		
PCT	-.390	-.381	-.417	-.119	-.234	-.297	-.080	-.126	.357	.001	.248	-.223	1.000	
MYD	-.077	-.143	-.070	-.195	.731	.633	.460	.216	.228	.326	-.221	.821	-.147	1.000

* $\alpha = 0.05$ $r = \pm 0.341$

$\alpha = 0.01$ $r = \pm 0.438$

at a 0.05 significance level with all of the physical properties except milling yield and to a high degree with bulk density and true density.

Referring to the summary of correlations in Table 11, note that the pearling index, which is the industry standard with the Strong-Scott Barley Pearler, correlates with the particle size reduction indicators of the 0.01 significance level but correlates with only the pearlograph area of the energy indicator group. Meanwhile, the pearlograph area correlates with the particle size reduction indicators and also correlates with each of the energy indicators including the pearling index. This tends to say that the pearlograph area is a good indication of the overall energy required for pearling or grinding and a good indication of the particle size reduction relationships. The pearlograph area also shows good correlations with the physical properties with the exception of protein content. The pearling index showed good correlations with all physical properties except milling yield. It should be noted the best correlation with bulk density was the pearlograph area while true density was with the pearling index. The best indicator of 1000 kernel weight and milling yield appears to be the peak torque measurement and protein content correlated best with the number 10 sieve measurement.

12% Level: 12% level contains the data collected from tests run on seven varieties of wheat all at approximately 12% moisture content. As summary of the results of the analysis of correlation for the 12% level is shown in Table 12. Looking first at the particle size reduction indicators, one notes that the pan sieve does not correlate with any of the other sieve sizes at this moisture level. Noting the fact that at all moisture levels combined (refer to Table 10), the pan sieve had significant correlation at the 0.05 level. One can conclude that moisture content affects the outcome of the pan sieve indicator in a different way than each of the other sieve sizes when used in this configuration. The number 10 sieve correlated to a high degree with all of the energy indicators, with wattmeter area being the highest. Peak watts correlated with all of the particle size reduction indicators but only at the 0.05 significance level. The physical properties correlation between each other remained fairly constant. The pearlograph area correlated with all of the other energy indicators, with the pearling index and with the physical properties of bulk density, true density and 1000 kernel weight. One can note a marked decrease in correlation between the pearlograph area and the particle size indicators at this increased moisture level, compared with the 9% moisture content level (refer to Table 11). Looking at the pearling index, one notes the high correlation between the pan sieve and the pearling index. This is even more significant in view of the pan sieve not correlating well with the other sieve sizes. Moisture content has affected the particle size correlations and since

Table 12. Correlation Coefficients for All Hardness Indicators at a 12% Moisture Level.*

Variable	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI	BDN	TDN	KWT	PCT	MYD
S10	1.000													
S14	.903	1.000												
S20	.908	.945	1.000											
PAN	.116	.194	.129	1.000										
PTQ	-.450	-.264	-.222	.306	1.000									
PWT	-.594	-.354	-.411	.340	.818	1.000								
AAP	-.555	-.429	-.329	-.313	.694	.449	1.000							
AAW	-.724	-.625	-.644	-.243	.368	.602	.580	1.000						
PLI	-.451	-.487	-.398	-.873	-.149	-.147	.522	.473	1.000					
BDN	-.447	-.295	-.242	-.612	.321	.293	.762	.603	.751	1.000				
TDN	-.426	-.405	-.303	-.664	.122	-.068	.746	.428	.847	.830	1.000			
KWT	-.479	-.221	-.252	.036	.749	.861	.561	.592	.080	.628	.171	1.000		
PCT	-.372	-.344	-.289	-.226	.011	-.006	.240	.158	.360	.001	.248	-.223	1.000	
MYD	-.169	.036	.010	-.012	.702	.759	.247	.367	-.067	.326	-.221	.821	.147	1.000

* $\alpha = 0.05$ $r = \pm 0.340$
$\alpha = 0.01$ $r = \pm 0.447$

the pearling index is based on a sieve size, one may conclude that the moisture content will effect the pearling index to a great extent also. The wattmeter area indicator seems to correlate the best among all of the other indicators at this moisture level. The wattmeter area correlated fairly well with the pearlograph area and both correlated at approximately the same level with the pearling index. However, looking only at the energy indicators and the physical properties, the pearlograph area appears to be more desirable with generally higher correlation coefficients with the physical properties. Bulk density was best indicated by the pearlograph area at this moisture level and true density by the pearling index. The peak watts best correlated with both 1000 kernel weight and milling yield, while protein content correlated best with the number 10 sieve.

15% Level: 15% level contains the data collected from tests run on seven varieties of wheat all at approximately 15% moisture content. A summary of the results of the analysis of correlation for 15% level is shown in Table 13. The particle size reduction indicators show a marked decrease in correlation among each other. Although still significant, one notes large drops (for example from 0.903 to 0.691 for the number 10 sieve versus the number 14 sieve) among all of the screen sizes and a slight increase between the screen sizes and the pan sieve compared to 12% level (Table 12).

These large drops seem to indicate that an increase in

Table 13. Correlation Coefficients for All Hardness Indicators at a 15% Moisture Level.*

Variables	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI	BDN	TDN	KWT	PCT	MYD
S10	1.000													
S14	.691	1.000												
S20	.561	.733	1.000											
PAN	-.416	-.235	-.362	1.000										
PTQ	-.773	-.478	-.235	.547	1.000									
PWT	-.730	-.270	-.195	.568	.928	1.000								
AAP	-.355	-.197	.248	-.210	.547	.429	1.000							
AAW	-.634	-.204	-.054	.269	.783	.817	.705	1.000						
PLI	.230	.052	.276	-.880	-.453	-.532	.331	-.139	1.000					
BDN	-.037	.074	.557	-.554	.208	.125	.765	.341	.565	1.000				
TDN	.147	.015	.485	-.714	-.191	-.320	.458	-.097	.735	.830	1.000			
KWT	-.553	-.176	.145	.177	.845	.834	.726	.780	-.159	.628	.172	1.000		
PCT	-.066	.097	.023	-.272	-.255	-.126	-.171	-.049	.355	.001	.248	-.223	1.000	
MYD	-.426	.010	.122	.353	.868	.879	.586	.821	-.367	.326	-.221	.841	-.147	1.000

* $\alpha = 0.05$ $r = \pm 0.341$
$\alpha = 0.01$ $r = \pm 0.453$

moisture content tends to cause less agreement between the particle size reduction indicators. The energy indicators all correlate between each other about the same. The number 10 sieve correlated fairly well with all of the energy indicators. None of the energy indicators correlated with all of the particle size reduction indicators. However, the peak torque measurement was the best among the energy indicators. Peak torque also seems to be the best indicator at this moisture level as it correlated well with the other energy indicators, the pearling index and also 1000 kernel weight and milling yield. Bulk density was best indicated by the pearlograph area; true density and protein content by the pearling index. Note that the number 10 sieve, number 14 sieve and the number 20 sieve all have positive correlations with the pearling index at this moisture level. This is the inverse of what is expected as pearling index is based on the amount of particles larger than the number 10 sieve. Therefore, it may be concluded that the moisture content has a large effect on the pearling index.

Considering the correlation coefficients at each moisture level, one can note that in general, as the moisture content increases, the correlation coefficients for the particle size reduction indicators (number 10 sieve, number 14 sieve, number 20 sieve and pan sieve) drop. This indicates that these indicators are affected to a large degree by the moisture content. Also, as the pearling index is based on a particle size reduction relationship, it will also be affected. This supports work done by Katz, Collins and Cardwell (1959). Comparing the moisture levels, one cannot see any general changes in the correlation coefficients of the energy or the physical property indicators. The summary of all samples at all moisture levels (Table 10) supports work done by Chung (1971) and tends to point to the pearlograph area as being the best overall indicator of hardness -- as indicated by the high correlation with all of the other hardness indicators. It also shows good correlation with all of the physical properties except protein content. The analysis of correlations done at each moisture level pointed out the large moisture effect on the pearling index. Comparing the three moisture levels, approximately 9% moisture content seems to produce the best correlation coefficients for the pearlograph area. Nine percent moisture also produced the greatest correlation between the pearlograph area and the pearling index. Increasing the moisture content produced less of an effect on the pearlograph area indicator than the pearling index as shown by the approximately constant correlations between the pearlograph area and the physical properties. Milling yield was the only physical property that showed an effect of moisture with a drop at the 12% level and approximately the same correlations at the 9% and 15% level. The pearling index showed a marked decrease in correlations with the physical properties with an increase in moisture.

It appears that the best moisture content for hardness tests using the pearlograph method would be approximately 9%. This moisture level produced generally the highest correlation coefficients with other energy particle size reduction indicators and physical properties. It can be used to directly indicate the physical properties of bulk density, true density, 1000 kernel weight, and milling yield as shown in Table 11. Milling yield could also be indicated indirectly by the peak torque (obtainable from the pearlograph area). Protein content cannot be predicted by either the pearlograph area method or the pearling index. The number 10 sieve indicated a significant correlation with protein content but it was of a low value of only 0.390.

Hardness Indication Selection

Based on the results of this study, the pearlograph area is selected as the best indicator of wheat hardness. The pearlograph area showed a high variety measuring ability with a low moisture variation. It also showed good variety separation characteristics as indicated indirectly by the peak pearlograph torque. Moisture content has less effect on the pearlograph area than other indicators as shown by the correlation coefficients. The pearlograph area is also applicable to a direct reading hardness indicator that would be fast, efficient, economical and whose results should not vary greatly between laboratories. This selection agrees with the results of Chung (1971).

Proposed Standard Hardness Test

The following procedure is proposed as a standard for wheat hardness tests using the pearlograph area method:

Equipment

1. Modified Strong-Scott Barley Pearler equipped with instrumentation necessary to produce pearlograph (Refer to Figure 15 and to the Investigation section).
2. Balance sensitive to 0.01 gram.
3. Stop watch or timer of equivalent accuracy.

Methods

1. Each charge (40 gm) is weighed from cleaned unsized wheat with a moisture content in the 9% to 12% range that has been throughly mixed.
2. The charge is placed in the machine with stone running at full speed and recording instruments properly zeroed; eighty seconds later the sample release gate is opened; ten seconds later the motor is stopped.
3. Five determinations should be made on each sample.

Results

1. The area under the curve should be determined for each test, averaged and then converted to an energy unit.
2. The energy unit should be compared with Figure 16 to obtain the Soft-Hardness Number (Chung, 1971) for the

sample. The Soft-Hardness Number may also be obtained by equation 10.

$$S.H. = 0.1923\ (E_p) - 49.9 \qquad (10)$$

where

S.H. = Soft-Hardness Number

E_p = Pearlograph energy, Kg - m

The Soft-Hardness Number may be compared to table 14 to approximate the classification.

Table 14. Classes and Soft-Hardness Numbers of Wheat Tested

Class	Soft-Hardness Range	Number Average	Standard Deviation
SRW	23-33	27.09	3.04
SWW	26-31	28.62	1.52
Durum	32-39	35.64	2.18
HWW	34-46	40.50	3.41
HRS	37-49	43.54	3.91
HRW	47-57	52.24	3.14

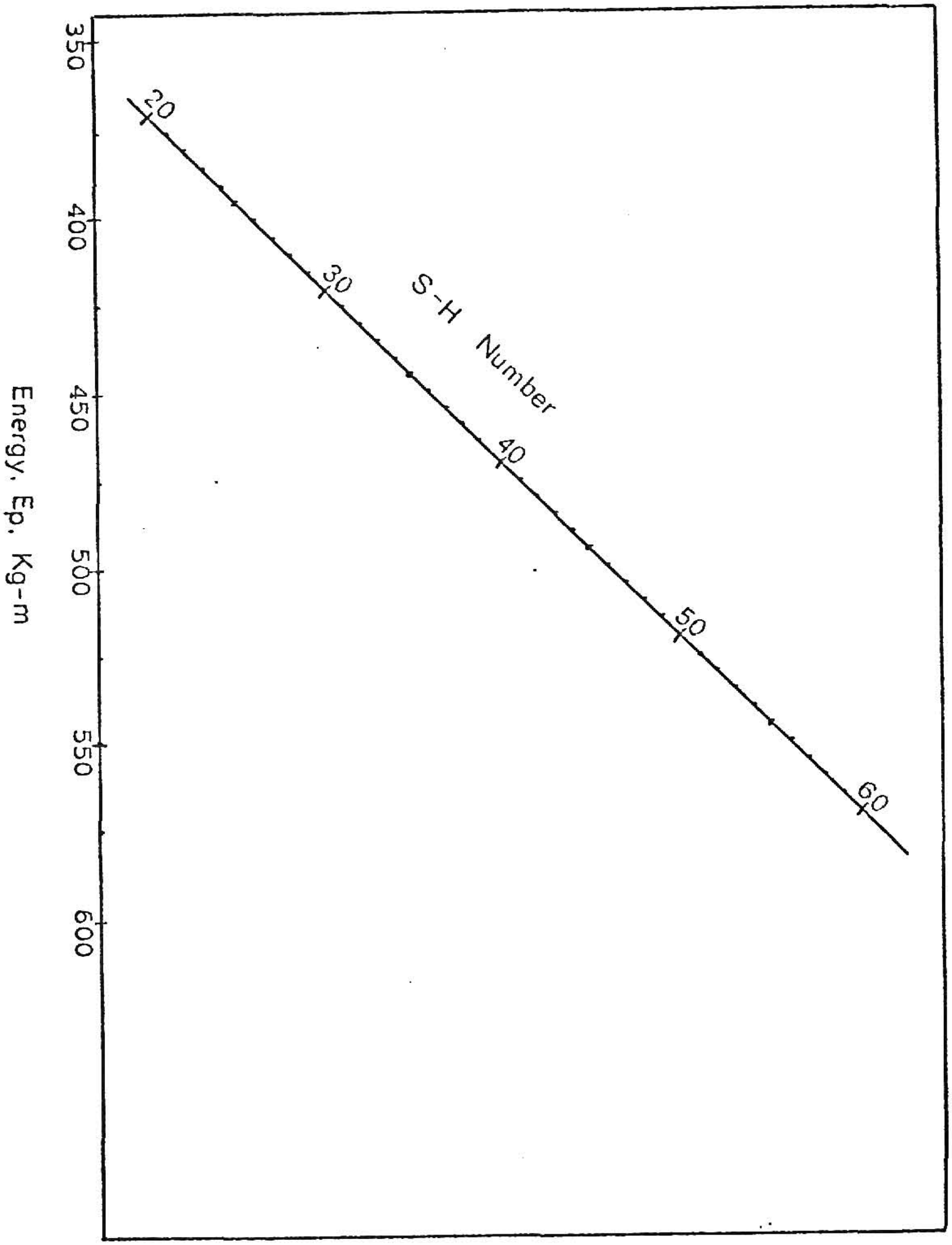

Figure 16. Pearlograph Energy vs. Soft-Hardness Number.

CONCLUSIONS

1. Peak pearlograph torque or pearlograph area are the two hardness level indicators best suited for direct hardness level measurements, based on the analysis of variance using the F test as the references; a high F ratio for variety effect with a low F ratio for moisture effect.
2. The electronic monitoring system used in this study was found to be unsatisfactory. The use of higher quality instruments could possibly increase the data correlations which would make the system useful.
3. The pan sieve produced the highest variety effect and the lowest moisture effect (with insignificant interaction) of the particle size analysis when using sieves in the configuration of this study.
4. The pearlograph area used for hardness differentiability would be most desirable as it shows less moisture effect and is approximately constant in the 9% to 12% moisture content range as shown by the coefficient of variations. If the pearling index or the number 14 sieve are to be used as differentiability indicators, the moisture content must be standardized to produce accurate results.
5. The pearlograph peak torque exibits the best variety separation characteristics as shown by Duncan's multiple range test. As the pearlograph peak torque can be obtained directly from the pearlograph area, the best overall hardness indica-

tor with respect to differentiability is the pearlograph area.

6. The best hardness indicator is the pearlograph area as shown by the correlation coefficients significant at the 0.01 significance with all of the remaining 13 indicators except protein content.
7. An increase in moisture content causes a decrease in the value of the correlation coefficients for the particle size reduction indicators and the pearling index. The energy correlation coefficients remain relatively constant.
8. The pearlograph area method of hardness measurements shows much less moisture effect in the 9% to 15% moisture content range than the pearling index or particle size reduction indicators.
9. The best moisture content for hardness tests using the pearlograph area method would be approximately 9% to 12%. This moisture range causes little moisture effect on the hardness indication.
10. The pearlograph area method of measuring wheat hardness is selected as the most desirable of the methods tested. This selection agrees with work done by Chung (1971). The pearlograph area can be a direct reading hardness indicator that would be fast, efficient, economical and whose results should be fairly consistant between laboratories. The pearlograph peak torque, which can be easily obtained from

the pearlograph area, could be used to classify wheat samples and give an indication of the resulting flour's uses and marketability.

11. Based on the results at this study, a standard hardness test procedure is proposed. This procedure should lead to an industry-wide standardization of wheat hardness tests using the pearlograph area method.

SUGGESTIONS FOR FUTURE RESEARCH

The investigation of the pearlograph area method of determining wheat hardness should be continued by conducting further studies as to moisture effect in the 5% to 20% moisture content range. The pearlograph area should be compared to a fairly constant physical property such as protein content or milling yield.

Procedures should be developed and standardized for the pearlograph area method and Soft-Hardness numbers (Chung, 1971) for all wheat classes. Tests of the repeatability of the methods by different operators should be conducted. Many different wheat varieties in each class should be tested to obtain a range of Soft-Hardness numbers (Chung, 1971) for each class of wheat.

An analysis of wheat should be done with the pearlograph area method on samples taken from flour mills. A relationship could then be developed between the Soft-Hardness number and the net cost of milling. The net cost of milling should include cost relating to the wheat being milled, such as initial price, power costs, wear and repair costs, subtracted from the selling price of the resulting flour. If such a relationship exists, the Soft-Hardness number could be used to predict the economic future of wheat samples.

REFERENCES

American Association of Cereal Chemists. 1968. Crude protein - improved Kjeldahl method for nitrate-free samples. Cereal Laboratory Methods. Method 46-11.

________ 1968. Crude protein - UDY dye method. Cereal Laboratory Methods. Method 46-14.

________ 1968. Particle size distribution of flour. Cereal Laboratory Methods. Method 50-10.

Anderson, R.A., V.F. Pfeifer and A.J. Peplinski. 1966. Measuring wheat kernel hardness by standardized grinding procedures. Cereal Science Today. 11:204-209.

Anderson, William A. and Erwin V. Zaretsky. 1970. Rolling-element bearings. Machine Design. 42(15):21-37.

Behar, M.F. 1932. Temperature and humidity measurement and control. Pittsburgh. Instruments Publishing Company.

Bennett, Edmond H. 1950. Kernel hardness in corn. I. A machine for the rapid determination of kernel hardness. Cereal Chemistry. 27:222-232.

________ 1950. Kernel hardness in corn II. A microscopic examination of hard and soft types of dent corn. Cereal Chemistry. 27:232-238.

Cargill. 1970. Feedstuffs. 42:22, 35.

Chapon, L. 1963. Anwendung des murbimeters zum studium der harte und der homogenitat der gersten. Brauwelt. 103:746-750.

Chung, Chang Joo. 1971. A development of method and basis for measuring wheat hardness. Kansas State University. Manhattan, Kansas.

Cutler, G.H. and G.A. Brinson. 1935. The granulation of whole wheat meal and a method of expressing it numerically. Cereal Chemistry. 12:120-129.

________, and W.W. Worzella. 1931. A modification of the Saunder's test for different purposes. American Society of Agronomy Journal. 23:1000-1009.

Greenaway, Walter T. 1969. A wheat hardness index. Cereal Science Today. 14(2):4-6.

Gaudin, A.M. and T.P. Meloy. 1962. Model and a comminution distribution equation for single fracture. AIME Transactions. 223:40.

Grosh, Gordon M. and Max Milner. 1959. Water penetration and internal cracking in tempered wheat grains. Cereal Chemistry. 36:260-273.

Handscombe, E. 1970. Electrical measuring instruments. London. Wykeham Publications, Ltd.

Hodgson, F.E. and J.H. Johnson. 1905. Tests of a single phase introduction motor. Manhattan, Kansas. Kansas State University Library.

Kallen, Howard P. 1961. Handbook of instrumentation and controls. New York. McGraw-Hill Book Company, Inc.

Katz, R., A.B. Cardwell, N.D. Collins and A.E. Hostetter. 1959. A new grain hardness tester. Cereal Chemistry. 36(5):393-401.

______, N.D. Collins and A.B. Cardwell. 1961. Hardness and moisture content of wheat kernels. Cereal Chemistry. 38:364-368.

Kent, N.L. 1966. Technology of cereals. Oxford. Pergamon Press.

Kramer, H.H. and H.R. Albrecht. 1948. The adaption to small samples of the pearling test for kernal hardness in wheat. Agronomy Journal. 40:422.

Kuprits, Ya. N. 1967. Technology of grain processing and provender milling. Translated from Russian.

Lebow. 1969. Torque and force transducers. Catalog. 200D:12.

Meppelink, E.K. 1968. Kernel hardness and its relation to mechanical and technological properties of wheat and flour. Annual Report. Institut voor graan, Neel En Brood Tno Wageningen, the Netherlands.

Mohsenin, Nuri N. 1966. Physical properties of pland and animal materials. University Park, Pennsylvania. The Pennsylvania State University Library.

Mular, A.L. 1962. Relationship among size modulus, size ratio and the integral rate at which fines are produced. AIME Transactions. 223:422-427.

McCluggage, Max E. 1943. Factors influencing the pearling test for kernel hardness in wheat. Cereal Chemistry. 20:686-700.

Popham, Richard A. and Richard H. Eyde. 1961. Relationship between physical characteristics and milling score of kernels of soft wheat varieties. Economic Botany. 15:140-155.

Rather, Howard C. 1942. Field Crops. New York. McGraw-Hill Book Company.

Roberts, H.F. 1910. A quantitative method for the determination of hardness in wheat. Kan. Agr. Exp. Sta. Bul. 167:371-390.

Saunders, H.A. and S. Humphries. 1928 The Saunders test. Nat. Inst. of Agr. Bottany Journal. 2:1

Schuhmann, R., Jr. 1960. Energy input and size distribution in comminution. AIME Transactions. 217:22.

Seeborg, E.F. 1953. Evaluation of wheat milling characteristics by laboratory methods. Trans. Am. Assoc. of Cereal Chemists. 11(1):1-5.

Shelef, Leora and Nuri N. Mohsenin. 1967. Evaluation of the modulus of elasticity of wheat grain. Cereal Chemistry. 44:392-402.

Shogren, M.D., and K.F. Finney. 1963. Correlations of certain properties of the alveogram with important hard winter wheat quality characteristics. Agronomy Journal. 55:21-24.

Smeets, Ing. H.S. and Heinz Cleve. 1956. Determination of conditioning by measuring softness. Milling Production. 21(4):5-16.

Tuve, G.L. and L.C. Domholdt. 1966. Engineering experimentation. New York. McGraw-Hill Book Company.

Taylor, J.W., B.B. Bayler and C.C. Fifield. 1939. A simple measure of kernel hardness in wheat. Journal of the American Society of Agronomy. 31:775-784.

Veinott, Cyril G. 1970. Fractional and subfractional horse-power electric motors. New York. McGraw-Hill Book Company.

Williams, Philip C. 1967. Relation of starch damage and related characteristics to kernel hardness in Austrailian wheat varieties. Cereal Chemistry. 44:383-391.

Zoerb, G.C. and C.W. Hall. 1960. Some mechanical and rheological properties of grains. Journal Ag. Engg. Res. 5(1):83-93.

APPENDIX A

EXPERIMENTAL DATA

Table 15. Complete Experimental Data Part One.*

I.D. Number	Class	Variety	Location of Growth	Moisture Content	BDN	TDN	KWT	PCT	MYD
11	HRW	Bezosztaja	Pullman, Washington	9.32	65.1	1.388	43.916	9.9	68.5
21	"	"	"	12.23	65.1	1.388	43.916	9.9	68.5
31	"	"	"	15.37	65.1	1.388	43.916	9.9	68.5
12	HRS	Justin	Sidney, Montana	9.00	60.0	1.359	33.561	14.5	66.9
22	"	"	"	12.45	60.0	1.359	33.561	14.5	66.9
32	"	"	"	15.16	60.0	1.359	33.561	14.5	66.9
13	SWW	Omar	Walla Walla, Washington	9.20	57.8	1.348	24.145	10.9	61.3
23	"	"	"	11.80	57.8	1.348	24.145	10.9	61.3
33	"	"	"	15.09	57.8	1.348	24.145	10.9	61.3
14	Durum	Leeds	Fargo,N.D.	9.07	62.4	1.369	32.749	13.3	**
24	"	"	"	11.81	62.4	1.369	32.749	13.3	**
34	"	"	"	15.11	62.4	1.369	32.749	13.3	**
15	Durum	Lakota	Fargo,N.D.	8.78	61.0	1.359	29.506	11.5	**

(Table 15 Cont.)

I.D. Number	Class	Variety	Location of Growth	Moisture Content	BDN	TDN	KWT	PCT	MYD
25	Durum	Lakota	Fargo, N.D.	11.62	61.0	1.359	29.506	11.5	**
35	"	"	"	14.62	61.0	1.359	29.506	11.5	**
16	HWW	Burt	Farmington, Washington	9.05	61.3	1.356	33.043	10.3	67.6
26	"	"	"	11.70	61.3	1.356	33.043	10.3	67.6
36	"	"	"	14.82	61.3	1.356	33.043	10.3	67.6
17	SRW	Reed	Wooster, Ohio	9.04	56.8	1.273	35.301	10.2	69.4
27	"	"	"	11.92	56.8	1.273	35.301	10.2	69.4
37	"	"	"	15.46	56.8	1.273	35.301	10.2	69.4

*Explaination of headings

Moisture Content expressed in percent.
BDN = Bulk density, lbs/bu.
TDN = True density, gms/c.c.
KWT = 1000 kernel weight, grams.
PCT = Protein content, percent.
MYD = Milling Yield, percent.

**Milling yield test not performed on Durum wheats by commercial labs.

Table 16. Complete Experimental Data Part Two.*

Var.	Rep.	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI
11	1	0.27	0.04	0.03	10.78	6.57	160	4105	2.136	65.450
11	2	0.20	0.03	0.27	11.12	6.34	159	4217	2.103	65.050
11	3	0.11	0.06	0.18	11.12	6.59	159	4272	2.030	66.425
11	4	0.36	0.23	0.25	12.49	6.53	156	4176	1.936	66.375
11	5	0.22	0.11	0.15	10.43	6.52	158	4228	1.996	66.325
21	1	0.15	0.19	0.21	13.04	6.28	170	4072	1.220	70.432
21	2	0.16	0.21	0.04	11.32	6.11	167	3878	2.160	70.225
21	3	0.07	0.05	0.02	10.70	6.13	167	3973	2.220	69.975
21	4	0.25	0.12	0.27	10.81	6.10	165	3976	2.220	69.025
21	5	0.13	0.13	0.07	11.40	6.15	164	3985	2.280	69.350
31	1	0.20	0.22	0.31	9.90	6.22	160	4218	2.093	68.075
31	2	0.31	0.23	0.34	9.88	6.02	155	3891	1.973	70.500
31	3	0.19	0.20	0.26	11.06	6.18	158	4099	2.043	68.725
31	4	0.44	0.23	0.38	10.50	6.17	158	4221	2.060	67.975
31	5	0.34	0.18	0.34	10.80	6.19	154	4068	1.926	69.000
12	1	0.49	0.16	0.21	11.91	5.83	154	3573	1.943	58.775
12	2	0.43	0.12	0.22	13.35	5.68	153	3499	1.930	58.500
12	3	0.56	0.18	0.31	15.04	5.82	150	3631	1.940	57.500
12	4	0.49	0.24	0.21	14.00	5.86	150	3595	1.910	58.450
12	5	0.48	0.28	0.16	14.45	5.95	149	3774	1.993	57.175
22	1	0.30	0.10	0.16	11.93	6.09	163	3748	2.090	65.975
22	2	0.22	0.05	0.10	14.72	6.03	161	3921	2.150	63.725
22	3	0.29	0.11	0.10	12.61	6.19	160	3959	2.130	64.350
22	4	0.15	0.05	0.06	12.60	6.07	159	3948	2.130	64.925
22	5	0.17	0.04	0.07	11.10	6.22	160	3756	2.020	66.250

(Table 16 Cont.)

Var.	Rep.	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI
32	1	0.23	0.20	0.20	11.54	5.80	150	3786	2.000	66.800
32	2	0.38	0.28	0.30	11.22	5.67	149	3456	1.850	68.675
32	3	0.28	0.19	0.18	12.12	5.68	150	3520	1.896	66.625
32	4	0.31	0.27	0.20	10.97	5.70	147	3471	1.886	67.400
32	5	0.37	0.14	0.23	12.83	5.87	150	3706	1.930	66.200
13	1	1.92	1.74	0.70	14.41	4.82	144	3082	1.936	38.300
13	2	1.74	1.56	0.66	15.02	4.78	140	3054	1.883	40.550
13	3	1.81	1.75	0.81	16.80	4.88	143	3158	2.030	40.000
13	4	1.45	1.44	0.73	14.82	4.87	142	3102	1.860	42.950
13	5	1.41	1.55	0.80	14.99	5.10	148	3095	1.820	43.675
23	1	1.05	0.67	0.34	13.69	4.68	141	3121	1.873	58.750
23	2	0.93	0.56	0.35	14.41	4.68	142	3250	1.890	58.250
23	3	1.02	0.44	0.30	13.32	4.80	145	3209	2.130	58.350
23	4	1.10	0.65	0.36	14.64	4.75	143	3209	1.953	57.250
23	5	1.16	0.54	0.42	12.82	4.58	138	3147	1.903	57.300
33	1	0.78	0.37	0.30	10.72	5.02	128	3364	1.740	66.500
33	2	1.00	0.29	0.18	10.42	4.79	126	3223	1.676	65.975
33	3	0.60	0.34	0.19	11.81	4.93	125	3295	1.710	66.150
33	4	0.75	0.35	0.28	10.87	5.01	128	3363	1.710	66.100
33	5	0.77	0.32	0.21	10.82	4.98	125	3253	1.640	66.925
14	1	1.07	1.14	0.47	11.85	5.01	135	3357	1.783	62.825
14	2	1.16	1.21	0.49	12.08	4.80	137	3414	1.870	61.125
14	3	1.07	0.97	0.47	10.74	4.95	142	3399	1.926	62.050
14	4	1.40	1.30	0.50	10.66	4.90	140	3441	1.923	61.200
14	5	1.29	1.32	0.54	10.84	5.06	140	3605	1.943	60.675

(Table 16 Cont.)

Var.	Rep.	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI
24	1	0.97	0.84	0.46	11.38	4.92	152	3600	2.076	71.075
24	2	0.92	0.77	0.44	9.52	4.78	151	3533	2.163	71.075
24	3	0.72	0.73	0.50	9.87	4.87	150	3431	2.063	72.175
24	4	0.85	0.61	0.42	8.71	4.74	151	3427	2.110	72.250
24	5	0.80	0.74	0.41	8.01	4.66	148	3297	2.000	72.325
34	1	0.80	0.59	0.46	7.27	5.03	139	3575	1.880	73.825
34	2	0.84	0.70	0.45	7.48	4.95	138	3693	1.960	73.000
34	3	1.02	0.70	0.48	8.35	5.11	140	3639	1.906	72.500
34	4	0.71	0.60	0.55	7.65	5.18	140	3637	1.863	73.700
34	5	0.81	0.54	0.40	7.61	5.21	139	3713	1.856	72.950
15	1	0.88	0.27	0.17	11.60	4.89	140	3442	1.956	64.225
15	2	0.83	0.25	0.27	11.43	4.74	139	3360	1.860	64.150
15	3	0.76	0.36	0.21	12.52	4.85	140	3504	1.976	64.325
15	4	0.55	0.20	0.21	11.00	4.87	140	3350	1.820	66.025
15	5	0.59	0.32	0.18	10.77	4.76	137	3373	1.870	65.225
25	1	0.60	0.36	0.16	7.61	4.72	149	3465	2.146	76.350
25	2	0.79	0.19	0.16	8.21	4.53	146	3310	2.096	76.450
25	3	0.70	0.18	0.19	7.23	4.58	144	3348	2.060	76.625
25	4	0.67	0.23	0.16	8.47	4.56	148	3321	2.093	76.425
25	5	0.61	0.15	0.14	7.47	4.56	141	3499	2.086	75.425
35	1	0.69	0.38	0.34	8.16	5.23	132	4005	1.926	77.825
35	2	0.81	0.32	0.28	7.37	5.11	131	3713	1.830	78.350
35	3	0.58	0.19	0.20	8.12	5.35	131	3542	1.946	77.350
35	4	0.57	0.20	0.20	6.53	5.26	133	3728	1.793	78.775
35	5	0.66	0.21	0.20	7.01	5.42	135	4013	1.946	77.150

(Table 16 Cont.)

Var.	Rep.	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI
16	1	2.60	2.38	1.14	12.72	5.50	153	3490	2.036	48.800
16	2	2.95	2.84	1.41	12.56	5.52	141	3605	1.896	46.000
16	3	2.72	2.26	1.30	11.72	5.62	141	3484	1.767	49.425
16	4	2.92	2.46	1.33	12.39	5.79	140	3720	1.820	48.175
16	5	2.78	2.28	1.00	10.92	5.76	139	3650	1.796	50.350
26	1	1.60	1.27	0.77	10.87	5.49	151	3750	2.113	59.500
26	2	1.52	1.07	0.70	10.21	5.28	144	3374	1.866	62.975
26	3	1.33	0.95	0.75	11.21	5.60	147	3567	1.913	62.575
26	4	1.69	1.01	0.73	11.07	5.65	148	3689	1.910	61.700
26	5	1.44	1.18	0.82	11.29	5.81	148	3855	1.913	60.175
36	1	1.11	0.56	0.43	10.81	5.32	136	3536	1.763	65.825
36	2	1.08	0.37	0.42	10.68	5.29	137	3573	1.826	65.225
36	3	0.91	0.50	0.46	9.98	5.39	138	3587	1.813	65.175
36	4	1.01	0.54	0.50	11.66	5.57	139	3607	1.820	64.525
36	5	0.88	0.58	0.54	10.69	5.52	140	3749	1.876	63.625
17	1	2.04	1.77	0.80	16.32	5.68	160	3328	2.080	32.575
17	2	1.86	1.64	0.69	13.94	5.42	156	3053	1.856	37.450
17	3	1.98	1.70	0.76	17.01	5.62	158	3227	1.936	33.750
17	4	1.87	1.63	0.85	17.26	5.61	158	3092	1.826	36.375
17	5	1.89	1.84	1.05	18.67	5.58	159	3144	2.000	34.750
27	1	0.96	0.84	0.37	16.27	5.57	164	3120	2.023	46.225
27	2	1.14	0.85	0.39	13.27	5.34	160	3010	1.976	45.975
27	3	1.12	0.69	0.60	17.93	5.49	161	2990	2.000	45.375
27	4	1.29	0.84	0.46	15.41	5.38	160	2960	2.036	45.550
27	5	0.79	0.75	0.35	17.96	5.29	159	2902	1.993	45.675

(Table 16 Cont.)

Var.	Rep.	S10	S14	S20	PAN	PTQ	PWT	AAP	AAW	PLI
37	1	0.29	0.34	0.28	21.05	6.13	161	3707	2.073	56.275
37	2	0.46	0.37	0.16	15.09	5.98	160	3457	1.963	57.550
37	3	0.44	0.31	0.21	14.92	6.00	160	3584	2.036	55.325
37	4	0.32	0.29	0.14	14.22	5.95	160	3455	1.926	57.000
37	5	0.43	0.34	0.06	13.24	5.87	159	3454	1.950	56.075

*Explaination of Headings

Var. = Variety and location; refer to Table 15.
Rep. = Replication.
S10, S14, S20, PAN = Cumulative oversizes in grams for Tyler sieve numbers 10, 14, 20 and PAN, respectively.
PTQ = Pearlograph peak torque.
PWT = Pearlograph peak watts.
AAP = Pearlograph area.
AAW = Wattmeter area.
PLI = Pearling index.

MODIFICATION OF THE STRONG-SCOTT BARLEY PEARLER FOR WHEAT HARDNESS TESTS

by

DENNIS K. KUHLMAN

B.S., Kansas State University, 1970

AN ABSTRACT OF
A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1975

The hardness of a sample of wheat is of interest, both scientifically and economically. Processors (millers) are interested in an accurate hardness tester which would enable them to estimate milling power requirements and repair costs for a wheat sample. Plant breeders want to produce a grain that has high protein content but is not exceptionally hard.

Hardness may be determined by grinding, cutting, pearling, crushing or indenting wheat kernels. There are many methods of determining hardness that can be found in the literature. Most of these methods involve laborious and time-consuming operations. The pearling technique was introduced which yields a hardness indicator called the pearling index. The pearling indexes do not show good differentiability, vary greatly among laboratories, and are affected by the size factor of kernels.

An attempt was made to improve the pearling technique by modifing it into the pearlograph technique. The pearlograph is a continuous measure of the pearler torque, which yields the total pearling energy when integrated with respect to time. Due to inadequacies noted with the pearlograph, the pearler was further modified by removing the laterial shaft motion, eleminating the need for temperature equalization, redesigning to remove the vibration on the release gate, and improving sample input. Experiments were run on the modified pearler to determine the pearlographs relation to other factors and its hardness indicating ability.

Twenty-one series of tests were conducted with each series consisting of five replications for studying the effects of two factors with the modified pearler: moisture content of the sample and variety or classification of the sample. The wheat samples used consisted of seven varieties representing six hardness classes. The seven varieties were tempered to three moisture levels (approximately 9%, 12% and 15%). The effects were measured by thirteen indicators from three parameters: particle size reduction, energy required and physical properties. These measurements were compared to each other and to the pearling index, which is the industry standard, by statistical methods.

Peak pearlograph torque and the pearlograph area are the two hardness level indicators best suited for direct hardness level measurements, based on the analysis of variance using the F test as the reference. The electronic monitoring system (peak watts and wattmeter area) was found to be unsatisfactory as used in this study.

The pan sieve produces the highest variety effect and the lowest moisture effect (with insignificant interaction) of the particle size reduction indicators when using sieves in the configuration of this study.

The pearlograph area method of measuring wheat hardness is selected as the most desirable of the methods tested. The pearlograph area can be a direct reading hardness indicator that would be fast, efficient, economical and whose results would be fairly constant between testing laboratories. The pearlograph peak torque (easily obtainable from pearlograph area) could be used to classify wheat samples and give an indication of the resulting flours marketability. The optimum moisture content for using the pearlograph is approximately 9% to 12% as this range produces little moisture effect. An increase in moisture content causes much less effect on the pearlograph area than on the other indicators tested.

Based on the results of this study, a standard hardness test procedure is proposed. This procedure should lead to an industry-wide standardization of wheat hardness tests using the pearlograph area method.